LEARNING MADE EASY

2nd Edition

Botany

for dummies

A Wiley Brand

Grasp the structure and function of plant cells

Understand different types of plants and where they grow

Learn why plants are essential to our climate

René Fester Kratz, PhD

Author of *Molecular & Cell Biology For Dummies*

Botany

2nd Edition

by René Fester Kratz, PhD

for dummies®
A Wiley Brand

Botany For Dummies®, 2nd Edition

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Introduction

Everybody's talking about green these days. Green technology, green energy, green lifestyles. It's no accident that the word *green* has come to symbolize a healthy world and sustainable habits. People use the word because it ties into visions of a green and growing world, lush with forests and fields of plants. This book is about the organisms that form the foundation of that green vision — the plants that surround us, support us, and make our world beautiful.

About This Book

Botany For Dummies, 2nd edition, is an introduction to the world of plants and their importance to the rest of life on earth. My goal is to present the concepts of plant biology in a clear and straightforward way, while I help you relate the science to your everyday life. I include lots of pictures of the processes, structures, and life cycles that you'd typically encounter in an introductory course in botany.

Botany is the study of plants, which covers a wide range of subjects, including their structure, function, patterns of inheritance, diversity, and importance to humans. Historically, botany also included the study of microbes and fungi, so I include a little bit about them here, too. I hope you'll be as surprised and intrigued as I was when I first began to study botany and realized that the seemingly simple world of plants was actually pulsing with life, mystery, and beauty.

Foolish Assumptions

As I wrote this book, I tried to imagine who you might be and what you might need in order to understand botany:

- A college biology major studying botany as part of your year-long freshman series.
- A college student taking an introductory botany class as a way to fulfill the science requirement for your degree in a nonscience field.

- Someone who just wants to know a little bit more about plants — you may be a gardener or a hiker who enjoys the beauty of plants and wants to know a little bit more about how they work.

Icons Used in This Book

The familiar *For Dummies* icons are used here to help guide you and give you new insights as you read the material.

TIP

This bull's-eye symbol lets you know what you need to do to get to the heart of the matter at hand. These icons mark information that helps you remember the facts being discussed or suggest a way to help you commit it to memory.

TECHNICAL STUFF

This information gives you extra information that isn't necessary to understand the topic. If you want to take your biology learning to a higher level, incorporate these paragraphs into your reading. If you want just the basics and do not want to be confused by the details, skip them.

REMEMBER

This little icon serves to jog your memory. The information spotlighted here is information you should permanently store in your biology file. If you want a quick review of biology, scan through the book reading the remember icons. No need for a chunky yellow highlighter.

WARNING

This icon alerts you to something that is possibly confusing. This information might be a common misconception shared by lots of people or a technical term that's used differently in certain situations. When you encounter one of these, slow down and check your understanding to make sure you aren't falling into a common mistake.

Beyond the Book

In addition to what you're reading right now, this book also comes with a free, access-anywhere Cheat Sheet that discusses the parts of a flower and the types of plant tissues. To view the Cheat Sheet, simply go to `www.dummies.com` and type **Botany For Dummies Cheat Sheet** in the Search box.

Where to Go from Here

Like all *For Dummies* books, each chapter in *Botany For Dummies,* 2nd Edition is self-contained, so you can pick up whenever you need it and jump into the topic you are working on. You can start anywhere in the book that you want. If you are reading this book for general interest, you might enjoy starting with the second-to-last part, “Embracing the Synergy of Plants and People.” If you’re taking a college class in botany, you’ll probably want to start at the beginning with the basics on plant cells, tissues, and organs.

I hope you enjoy your journey into the world of plants and find them as amazing and beautiful as I do!

1

Getting Started with Botany Basics

IN THIS PART . . .

Take a look at the most fundamental structure of plant bodies, the plant cell

Explore the basic organs of the plant body like roots, stems, and leaves

Discover the purpose behind flowers, cones, and fruits

Compare the role of seeds versus spores in plant reproduction

IN THIS CHAPTER

- **Building plants one cell at a time**
- **Finding out about how plants work**
- **Connecting plants and people**

Chapter 1

Exploring Botany

B*otany* is the study of plants, including plant structure, function, reproduction, diversity, inheritance, and more. Plants may seem like they're part of the background of your life, when really they're at the center. The food you eat, the clothes you wear, the materials that make up your home — all these things depend upon plants. Plants remove carbon dioxide from the atmosphere, helping to keep your planet from getting too warm for life as you know it. They provide homes for insects and other animals, filter impurities out of ground water, and help protect shorelines from erosion.

And beyond all these useful things plants do, they're just cool! Plants have many unique strategies that help them survive in all different kinds of environments. They trap and trick insects, grow in the ground or up in the rainforest canopy, and manage to survive everywhere from the glacial arctic to the hot, dry deserts. They seem so different from people, and yet when you really look at how plants grow and function, you'll be surprised at how similar they are to you. This chapter offers an overview of the science of botany, giving you a peek into the mysteries of plants.

Taking a Close Look at Plant Structure

You might not think so, but plants are a lot like you. Their bodies are made of cells (that are organized into tissues (see Chapter 2), and these tissues form the familiar plant organs of roots, stems, and leaves (see Chapter 3). Plant cells use the same basic chemistry as your cells, storing information in DNA, using carbohydrates for energy, and putting proteins to work. And your cells and plant cells are both *eukaryotic cells,* meaning they have a similar structure that includes a nucleus and cellular organelles.

Plants have many ways of reproducing themselves (see Chapter 4). When plants reproduce sexually, they make special reproductive cells called *spores*. Many familiar plants make a structure that's even better at starting the next generation — the *seed.* Seeds protect the plant embryos they carry and nourish them with stored food.

Many familiar plants reproduce sexually by producing showy flowers designed to attract animals to help spread their pollen around. Other flowering plants just dangle their flowers in the wind and let the wind do the work.

REMEMBER

Flowers contain the male and female parts of the plant that will participate in sexual reproduction.

Pollen comes from the male part of flowers, carrying and protecting the plant sperm. The female parts of flowers house the ovules that contain the eggs. *Pollination* occurs when pollen arrives at the female part of the flower. The pollen releases the sperm so that they can fuse with the egg, causing *fertilization,* and starting the next plant generation. After fertilization in flowering plants, the ovaries within the flowers develop into fruits (see Chapter 4). Some fruits are sweet and fleshy, inviting animals to come eat the fruit and then disperse the seeds. Other fruits are dry and designed to either float on the breeze, hitch a ride on some animal fur, or even explode to release their seeds. Whatever the method, the goal is the same — to find a nice, new home for the embryos inside the seed to grow.

Figuring Out Plant Functions

In addition to being made of cells and having similar chemistry, plants use many of the same strategies that you do to solve life's challenges. Both you and plants need a source of building material, called *matter,* to build the cells of your body, and you both need a source of *energy* so that you can build things and move around. And just like you, plants need to transport food and fluids around their bodies. Finally, you and plants both grow and develop, responding to changes in your environment.

Making and using food

The go-to source of matter and energy for all living things is food. Of course, one big difference between you and a plant is that you have to get your food by eating another organism, whereas plants can make their own.

Plants make their own food through the process of *photosynthesis* (see Chapter 5). Although the process of photosynthesis is pretty complex, you can get the main idea if you think of it like a recipe. The ingredients are carbon dioxide from the atmosphere and water taken up from the soil. You then follow these directions:

1. Use light energy from the sun to combine carbon dioxide and water, rearranging the atoms to form sugar and oxygen.
2. Serve sugar to all parts of the plant that need matter and energy and throw the oxygen gas away.
3. If you have leftovers, you can combine the sugars into starch to store some for later.

When plants want to use some of the sugar they've made to provide themselves with matter and energy, their cells do the same thing that your cells do with food, they break it down in a process called *cellular respiration* (see Chapter 6). Cellular respiration is a series of chemical reactions that basically unpack food molecules, making the matter and energy available to cells. When cells use cellular respiration to extract all the energy they can from food molecules, they release the waste matter as carbon dioxide and water.

Transporting materials

All the cells of a plant need food to provide them with matter and energy. Plants usually make sugars in their leaves, so they have to ship those sugars from the leaves to the rest of the plant. Likewise, plants take in water through their roots, but they need to get water to the entire plant, especially to the leaves, where it's needed for photosynthesis. So, just like you have veins and arteries to transport blood around your body, plants have vascular tissue that specializes in the transport of sugar and water (see Chapter 7).

REMEMBER

Plants transport dissolved sugars using a special type of tissue called *phloem*, and they transport water and dissolved minerals using a tissue called *xylem.*

Phloem transports sugar from the leaves where it's made through photosynthesis, to all parts of the plant that need it for growth or that will store it as starch for later. Xylem transports water from the roots up through the plant to supply all the cells with the water they need.

Responding to hormones

Yet another similarity between you and plants is that they use *hormones* to direct their growth and development (see Chapter 8).

Although plants never go through puberty (lucky plants!), they do undergo major developmental changes, such as when a seed switches from being dormant to beginning to grow or when a flowering plant decides it's the right time of year to start putting on a floral display. Plant hormones also direct responses like helping plants' shoots grow toward the light and causing plant roots to grow downward toward the pull of gravity.

Considering Plant Reproduction and Genetics

Plants grow like, well . . . weeds. That's because weeds are plants. (Okay, now I'm just being silly.) But seriously, plants grow when groups of cells at their tips, called *apical meristems,* divide in two to produce new cells. The process of cell division that adds new growth is called *mitosis* (see Chapter 9). Plants do mitosis pretty much the same way your cells do. Woody plants also do mitosis to grow wider, adding girth to tree trunks.

Plants also reproduce sexually, combining sperm and egg to make the next generation of plants. Plant life cycles are more complicated than those of humans (see Chapter 9), but, just like us, they can use a type of cell division called *meiosis* to produce cells that have half the genetic material of the parents. These cells ultimately give rise to the sperm and egg cells. Sperm and egg cells fuse, bringing together copies of the DNA from the parent plants.

REMEMBER

By following the inheritance of traits from one generation to the next through the science of *genetics* (see Chapter 10), scientists can figure out how plant genes interact with each other to determine the traits of a plant.

Planet Earth is filled with a glorious diversity of plants. Plants can be as tall as the mighty redwood tree or as small as the tip of a pin. They can grow so rapidly that they go from seed to seed in a month, or live for over a thousand years. Because plants moved onto the land over 400 million years ago, they've evolved to live in every type of environment (see Chapter 11): Today, plants grow in the deserts, in the rainforests, in the oceans, and up on mountains.

Exploring the Wide World of Plants

Botanists study all the different kinds of plants to understand how each one gets what it needs to survive and reproduce. They also compare the structures and DNA code of plants to figure out the relationships between plant groups and reconstruct how plants evolved (see Chapter 12). They've identified the closest relatives to plants (see Chapter 13) and studied how the ancestors of plants had to change in order to survive when they moved from the ocean to the land (see Chapter 14). To survive and reproduce outside of the oceans, plants needed to develop new strategies for managing water, delivering sperm, and protecting embryos.

Some plants developed flowers and fruits, whereas others evolved cones. Some plants learned how to lure insects in to help with pollination, whereas other plants developed ways to trap and kill insects as a source of minerals. With all these different strategies and environments, you can probably imagine that some pretty amazing plants are out there, from delicate mosses (see Chapter 14) to sturdy pine trees (see Chapter 15) and plants that produce colorful flowers (see Chapter 16). And in the soil around all these different plants the fungi grow (see Chapter 17), many of which form partnerships with plants called mycorrhizae.

REMEMBER

Mycorrhizal fungi form intimate connections with plant roots that enable sharing between plants and fungi. The plants provide food for the fungi, whereas the fungus helps the plant absorb more water and minerals from the soil. Without their mycorrhizal partners, most plants couldn't even survive.

Making Connections Between Plants and People

The lives of people are completely interwoven with the lives of plants:

- **People use plants to make clothing.** Cotton and flax plants are used to make cotton and linen clothing. Some of the dyes people use to give their clothing color also come from plants (see Chapter 18).
- **People get medicines from plants.** Digitalin for heart disease, aspirin to reduce fever, and artemisinin for malaria are just a few examples of the powerful drugs people have extracted from plants (see Chapter 18).
- **People use plants for building materials.** People use wood for houses, furniture, and tools, and they use straw as material for roofs or bricks.

- **People reduce their stress and improve their fitness by taking a walk and admiring the plants.** Seriously, reducing stress is important. Stress has major impacts on people's health. And for many people, nature has a soothing effect.
- **People grow plants for food.** The origins of human agriculture stretch back at least 10,000 years. And the switch from hunting and gathering to farming changed the entire structure of human societies (see Chapter 19).
- **People can modify plants to make them more nutritious or to make them produce medicines.** Genetically modified foods are very controversial, but they have benefits as well as risks (see Chapter 19).
- **Plants support the ecosystems of which people are a part.** Without plants to supply food to the web of life, what would you eat? (For more on this topic, see Chapter 20.)
- **Plants help keep water clean.** You probably hear people talking about wetlands, how they're important, and how they're disappearing at a rapid rate, thanks to development. Wetlands are communities with certain types of plants and soils. As the rain falls across areas where humans live, it picks up lawn fertilizers, motor oil from cars, poop from pets, and more. If this runoff flows through a wetland before it enters our streams and lakes, the plants and bacteria in the wetlands will remove lots of the dangerous substances on the way. Having wetlands to slow the flow of water also helps prevent flooding.

IN THIS CHAPTER

- Exploring plant cells
- Making more cells with meristems
- Comparing simple and complex tissues

Chapter 2

Peering at Plant Cells and Tissues

Plant structure and function depend on the cells and tissues that make up their organs. Plants grow from the tips of their branches and roots as cells divide to produce new cells. Cells differentiate, becoming specialized to perform specific functions and combining with other cells to form unique types of tissues in plants. This chapter presents the different types of cells, tissues, and tissue systems found in plants.

Building Cells from Four Types of Molecules

The molecules that form the structures in plant cells have many important functions for plants and people. Molecules are the building blocks that make up cells. You can think of molecules like little chemical Legos that are arranged and rearranged to build the structure of each living and growing cell. In multicellular organisms like plants, cells join together to form the tissues that make up the structure of the organism.

REMEMBER

The cells of all living things, including plant cells, are primarily made of four types of big molecules, called *macromolecules*:

- Carbohydrates
- Proteins
- Nucleic acids
- Lipids

Carbohydrates

Carbohydrates are commonly referred to as sugars, and the foods you can think of that are naturally sweet — like fruit, for example — are probably high in carbohydrates. Plant cells use carbohydrates for storing energy and also to provide structure to the cell.

Several types of carbohydrates are important to plant cells:

- **Many sweet tasting carbohydrates are smaller, simple sugars, called *monosaccharides* by scientists.** Glucose is an example of a monosaccharide. Glucose is extremely valuable to cells because it can be used as a fast source of energy. Glucose can exist in the linear form shown in Figure 2-1a, but in the water-filled environment of a cell, the molecule loops around and binds to itself, forming a ring-shaped structure (shown in Figure 2-1b).
- **Monosaccharides may form bonds with each other to form larger structures.**
  - When glucose bonds with fructose, the sugar found in fruit, they form the *disaccharide* sucrose, otherwise known as common table sugar (see Figure 2-1b). Plants make sucrose in their green structures and then ship it all around the plant body to provide matter and energy to all their cells.
  - Short chains of monosaccharides are called *oligosaccharides* (see Figure 2-1c). Oligosaccharides send signals to plant cells, triggering growth responses and defense mechanisms.
  - Long chains of monosaccharides form *polysaccharides* (see Figure 2-1d). You may have heard polysaccharides referred to as complex carbohydrates. Like monosaccharides, polysaccharides are important molecules for storing energy and building materials and then making them available to cells. For example, the starch found in rice, pasta, breads, and potatoes is a polysaccharide that's an important source of energy for both plants and people. Plants reinforce the structure of their cells with the polysaccharide cellulose, which is one of the major components of the cell wall that surrounds and supports plant cells.

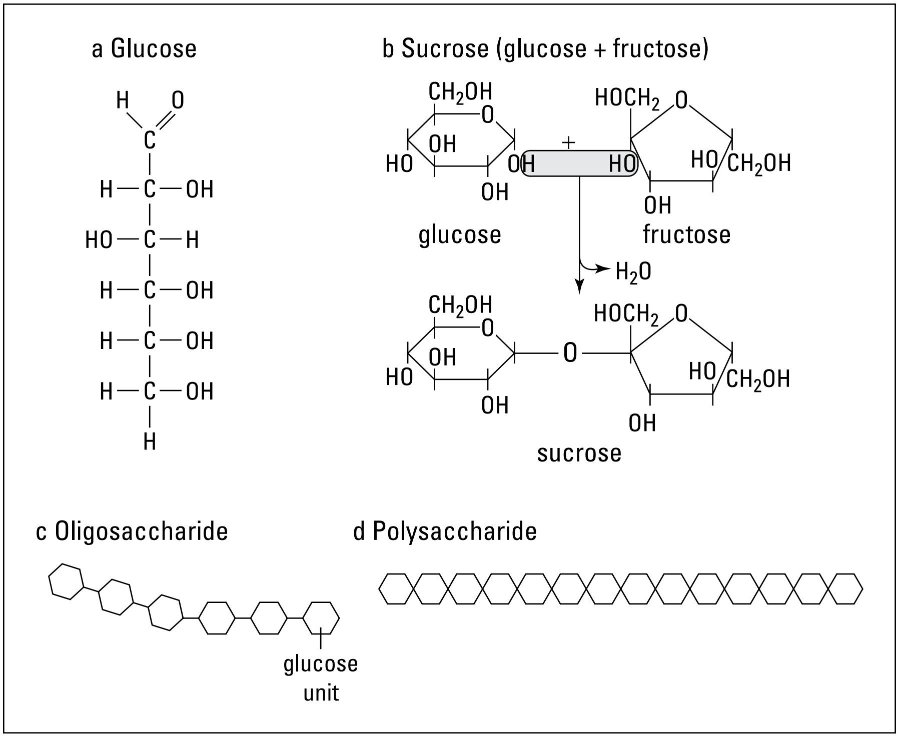

a Glucose
b Sucrose (glucose + fructose)
glucose
fructose
H_2O
sucrose
c Oligosaccharide
d Polysaccharide
glucose unit

FIGURE 2-1: Carbohydrates.

GET YOUR FIBER HERE!

Fruits and vegetables, as well as other plant foods like nuts and whole grains, are an excellent source of fiber. But what is fiber? And why do plants have it? *Fiber* is the common name for certain plant polysaccharides like the cellulose that surrounds and supports plant cells. Cellulose is a long chain of glucose molecules strung together, but because of the way the glucose molecules join together in cellulose, our digestive systems can't break them apart. When cellulose, or fiber, hits your digestive system, it just passes on through. Your body can't access the glucose molecules at all. So, all that undigested fiber passes into your large intestine and helps give mass to your, er, *waste*, which keeps your large intestine healthy and functioning normally. Fiber can help lower blood cholesterol, control blood sugar, and help people lose weight. So, be sure to include plenty of plants in your daily diet!

Proteins

Plant cells couldn't function without proteins. That's because proteins perform essential jobs in cells, moving materials around, creating scaffolding for the cell, helping chemical reactions, controlling information flow, and sending signals.

Each protein has a unique shape that helps it do its job. To make a protein, cells link *amino acids* with strong bonds called *peptide bonds* (shown in Figure 2-2), forming long chains of amino acids called *polypeptide chains*. The polypeptide chains fold up, either singly or in groups, to form the final shape of the functional protein.

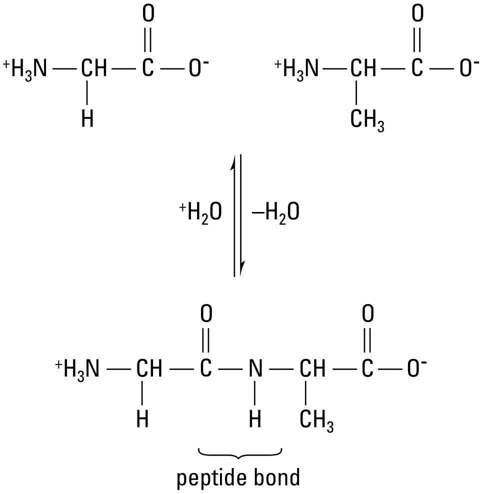


FIGURE 2-2: Amino acids link together to form proteins.

Proteins have so many functions in plant cells that a list could go on for two pages. Rather than overwhelm you with all those functions at once, I hit a few of the most important functions here and then introduce specific proteins as they're needed throughout the book:

- ***Enzymes* are proteins that speed up chemical reactions.** As they live and grow, plants are constantly building new molecules and breaking other molecules down. The speed of these chemical reactions by themselves wouldn't be fast enough to keep up with the pace of life. So plant cells, just like all cells, use enzymes to make those reactions happen exactly when plants need them.
- ***Structural proteins* support the cell.** Protein cables inside plant cells, called *cytoskeletal proteins,* provide supportive scaffolding from the inside. (For more details on cytoskeletal proteins, see the upcoming section "Scaffolding and

railroad tracks: The cytoskeleton," later in this chapter.) Outside the cell, proteins are woven into the plant *cell wall,* a protective layer that encases plant cells. (You can find out more about plant cell walls in the section "Rebar and concrete: Cell walls and extracellular matrices," later in this chapter.)

- ***Transport proteins* move materials into and within plant cells.** Plants need to move molecules in and out of their cells. Transport proteins located at the boundary of the cell help create passageways for these materials. Inside the cell, molecules and structures may use cytoskeletal proteins as tracks that allow them to move around the cell.
- ***Receptor* proteins help plant cells communicate.** In order to receive signals, such as hormones, plant cells need receptors that specifically recognize each signal. Receptors, which are usually proteins, can be located on the surfaces or insides of cells.

Nucleic acids

Even if you haven't heard the term *nucleic acids* before, I'm sure you've heard of DNA, which is short for *deoxyribonucleic acid.* Nucleic acids like DNA are molecular specialists in information: The molecules are a chemical code that stores information and can transfer it from one generation to the next.

Two types of nucleic acids are found in cells:

- **DNA stores the information that determines the structure and function of all cells on earth.** The structure and function of the cells lead to the traits of the organism, which is why people say that DNA determines your traits. People don't talk about plants much, but if they did, they'd say that DNA determines the traits of plants, too. You can think of DNA like the hard drive on a computer — it's the main place where information is stored. So, whether a plant becomes a mighty redwood or a tiny wildflower is ultimately encoded in the DNA of its cells. And just like the information in a computer, the information in DNA can be copied and transferred. When cells reproduce, they copy their DNA molecules and pass them on to the new cells.
- **RNA, or *ribonucleic acid,* is similar to DNA in structure, but more flexible in its functions.** Different types of RNA molecules perform different functions in cells: Some of them carry information around the cell, some of them help build proteins, and some of them control when proteins are made. In terms of information, RNAs are more like e-mails — they contain information, but they can travel around and cause things to happen.

Nucleic acids are made from *nucleotides*, which are complex molecules that consist of three parts (see Figure 2-3):

- **A 5-carbon sugar:** In RNA nucleotides, like the one shown in Figure 2-3, the sugar is *ribose*. In DNA nucleotides, the sugar is called *deoxyribose*. Deoxyribose looks just like ribose, except that it's missing one oxygen atom.
- **A phosphate group:** Phosphate groups contain a phosphorous atom surrounded by oxygen atoms. Some oxygen atoms have extra electrons, making them ionized and giving them a negative electrical charge. DNA and RNA molecules are negatively charged because of these phosphate groups.
- **A nitrogenous base:** Nitrogenous bases are ringed molecules that contain the element nitrogen. Five different nitrogenous bases are found in nucleotides: adenine (A), cytosine (C), guanine (G), thymine (T), and uracil (U). DNA nucleotides contain A, C, G, and T, whereas RNA nucleotides contain A, C, G, and U.

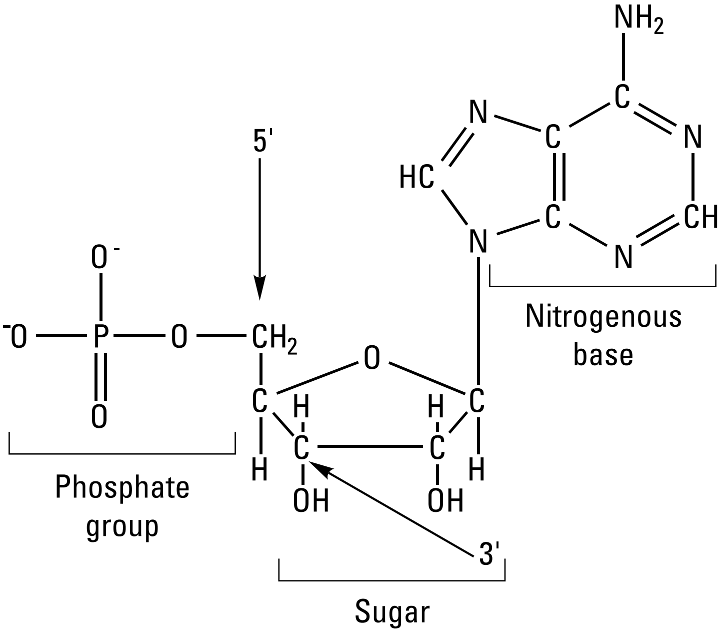


FIGURE 2-3: Structure of a nucleotide (adenosine monophosphate, an RNA nucleotide).

Cells make DNA and RNA molecules by forming covalent bonds between nucleotides (see Figure 2-4). The chains formed by this process are called *polynucleotides*.

REMEMBER

DNA molecules contain two polynucleotides attached to each other by hydrogen bonds, whereas RNA molecules contain just one polynucleotide chain. The two polynucleotide strands of DNA attach to each other by hydrogen bonds between the bases A and T, and between the bases C and G, forming base pairs that look like the rungs of a ladder. The two strands twist around each other, forming the double helix of DNA.

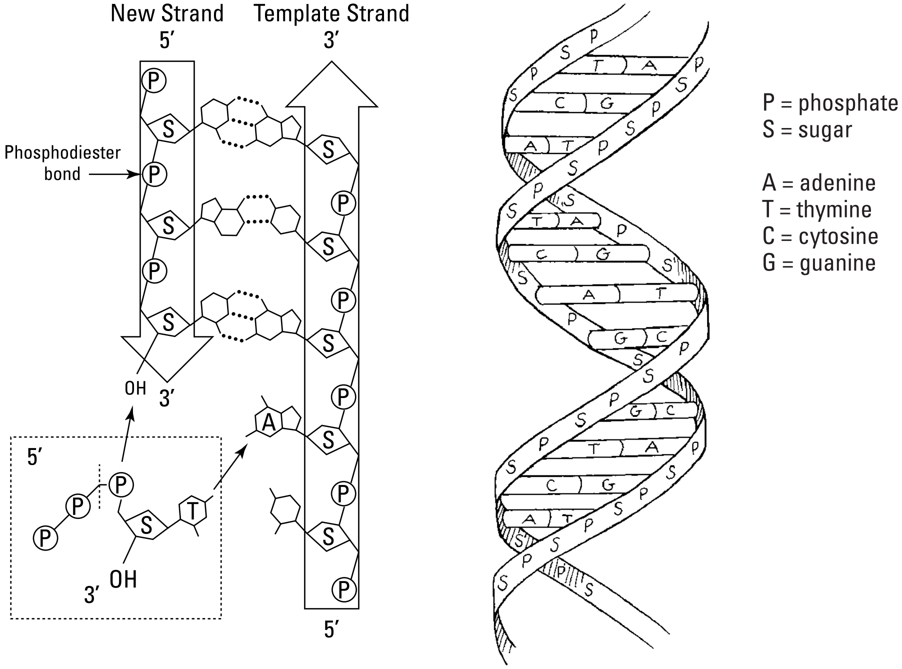


FIGURE 2-4: Polynucleotide chains.

The information code in DNA and RNA molecules depends upon the order of nitrogenous bases in the polynucleotide. Just like the 26 letters of the alphabet can write words, the pattern of chemical molecules A, C, G, and T spell out the information in DNA molecules, like the one shown in Figure 2-4. This information contains the instructions for building proteins and RNA molecules that determine the structure and function of cells. Similarly, the information in RNA molecules is spelled out in the order of the molecules A, C, G, and U.

REMEMBER

The genetic information of all cells is stored in molecules of DNA that are folded around proteins to form structures called *chromosomes*. The order, or *sequence*, of the four kinds of nucleotides within each chromosome spell out the instructions that determine the traits of the organism.

Lipids

Lipids are molecules that don't mix with water, like fats, oils, and waxes. Cells, including those of plants, use lipids to create boundaries around and within cells. Lipids are also an excellent way to store energy and building materials for growth, and many plants, including olives, nuts, and even corn use oils as storage molecules.

REMEMBER

Molecules like lipids that don't mix with water are called *hydrophobic*, which literally means *water-fearing*. In contrast, molecules that do mix with water are called *hydrophilic*, which means water-loving.

HUNGRY FOR HYDROCARBONS

The carbon-hydrogen bonds that make up lipid molecules store a great deal of usable energy. For example, you may have heard that fats have 9 calories per gram, whereas carbohydrates have 4 calories per gram. Gram for gram, fats store more than twice the amount of energy as carbs! But the human craving for hydrocarbons goes way beyond nutrition. When humans discovered the potential of these molecules, we completely redesigned our way of life around them. The use of oil and gas to light our world extended our usable time into the hours of darkness. We hunted several species of whale almost to extinction for the oil we could extract from their bodies. We drill for the crude oil formed by the decomposition of ancient life and dig for the coal produced from the remains of plants from the Carboniferous Period (coal is a carbon, but not a hydrocarbon). Our use of hydrocarbons expanded when we learned to harness their power to run machines. The Industrial Revolution transformed our landscapes as we built factories and railroads and expanded our cities. We could travel farther and build more than ever before.

Unfortunately, the side effects of this hydrocarbon habit are destruction of natural environments and pollution. One pollutant that's making itself felt today is the carbon dioxide (CO_2) released into the atmosphere when hydrocarbons are burned. Atmospheric CO_2 has increased steadily since the Industrial Revolution, and so have global temperatures. It turns out that CO_2 is a *greenhouse gas* that acts like a blanket and traps heat on the earth's surface. People today must simultaneously solve the problems brought on by our hydrocarbon-fueled growth and figure out how we're going to replace our favorite energy source when it's gone! No one knows what the full extent of the consequences will be for the environmental changes we've caused and whether we can reverse the dangerous trends we've set in motion. On the energy front, we're already searching for solutions — making our machines more fuel efficient at the same time that we try to develop alternative fuel strategies (like wind and solar). Only time will tell if our harnessing of hydrocarbons was too much of a good thing.

Four types of lipids are especially important in plant cells:

- **Triglycerides (fats and oils):** *Triglycerides* store energy and building materials for growth. The structure of fats and oils is basically the same (see Figure 2-5): a 3-carbon molecule called glycerol forms the backbone to which three fatty acids attach. Most plants store oils, not fats.

  The difference between whether a triglyceride is a fat or an oil depends on how many *unsaturated* bonds it has between its carbon and hydrogen atoms. Unsaturated bonds result from two carbon atoms sharing two pairs of electrons from each other, forming a *double bond* like the one shown in the bottom fatty acid in Figure 2-5. Carbon atoms that are doing a double handshake with each other can't bond to as many hydrogen atoms, so the bonds are considered "not full" or unsaturated with hydrogen. *Saturated fats* contain lots of carbon atoms joined with single bonds, like the straight chains of fatty acids in Figure 2-5. Saturated fat molecules, like those in butter, can pack tightly together and are solid at room temperature. Unsaturated fats, like those in plant oils, have bent fatty acid chains, so they don't pack as tightly and are liquid at room temperature.

- **Phospholipids:** Cells build boundaries called *membranes* out of *phospholipids.* (To sneak a peek at phospholipids in membranes, go to "Customs: Plasma membranes," later in this chapter.) Phospholipids are similar in structure to triglycerides, but one fatty acid chain is swapped for a hydrophilic head group. So, phospholipids have a dual nature — they're hydrophilic at one end, and hydrophobic at the other.

- **Steroids:** Several plant hormones are *steroids,* lipid molecules made of four connected carbon rings. These hormones, called *brassinosteroids,* control many aspects of plant growth and development and trigger responses that protect plants from stress.

- **Waxes:** Many plants use *waxes* as a protective coating on the surfaces of leaves and other structures. Waxes help prevent water loss and can protect plants from insects and fungal pathogens. Carnivorous plants use waxes to make themselves slippery so that flies and other insects will slide to their doom! Waxes are diverse structurally, but the backbone of a wax is a long chain of carbon and hydrogen that is similar to a fatty acid. Next time you notice the gloss on a leaf, chances are you're looking at a plant wax.

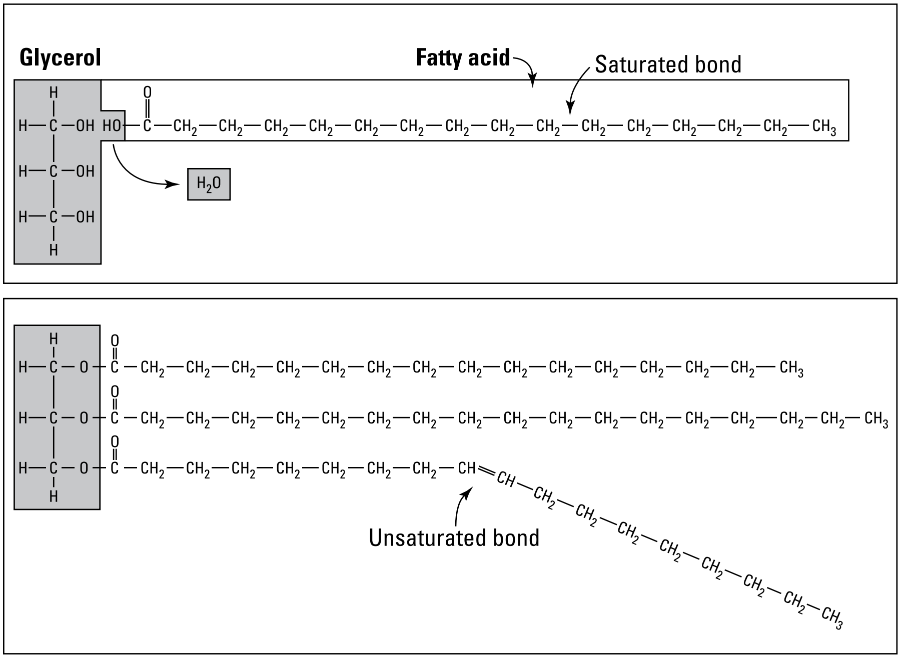


FIGURE 2-5: Saturated and unsaturated bonds in a typical triglyceride.

Entering the World of Cells

All living things, from tiny bacteria to giant redwood trees, are made of cells. Cells are the smallest things that have all the properties of life, including the ability to reproduce, respond to signals, grow, and transfer matter and energy with their environment. Figure 2-6 shows many of these functions and the structures that perform them in a plant cell.

Based on a comparison of fundamental cell chemistry and hereditary material, all cells on earth can be divided into three groups, called *domains.* You can think of these three domains as three main branches on the family tree of life on earth:

- **Eukarya:** Plants, animals, fungi, and protists
- **Bacteria:** Familiar, single-celled microorganisms, like the bacteria in your yogurt or the bacteria that cause human diseases
- **Archaea:** Single-celled microorganisms that are found in all types of environments, but were first discovered in extreme environments like hot springs

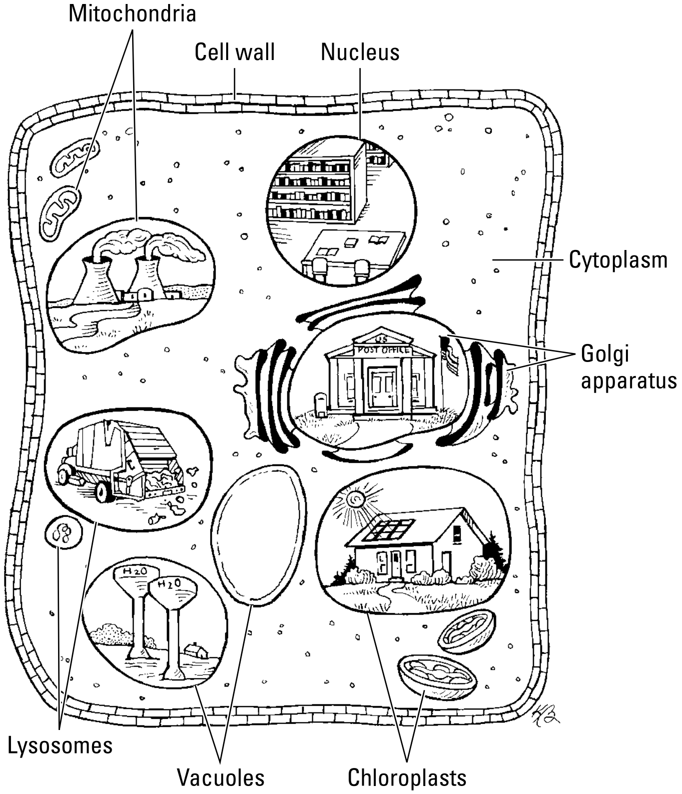


FIGURE 2-6: Plant cells perform all the functions of life.

In terms of cell structure, the cells of Bacteria and Archaea are very similar because they're both prokaryotic, while the cells of Eukarya are more complex because they're eukaryotic. (See the section "The Library: Storing Information in DNA," later in the chapter.)

The cells of organisms from all three domains have certain features in common. They all have a boundary that distinguishes the cell from the environment, they contain DNA, and they have the ability to make proteins. The next few sections present these common cell features in more detail.

Customs: Plasma membrane

The barrier that separates the inside of the cell from its environment is called the *plasma membrane* (see Figure 2-7). The plasma membrane is made of two layers of phospholipids, forming a *phospholipid bilayer* with the hydrophilic heads of the phospholipids pointing outward and the hydrophobic tails of the phospholipids sandwiched in the middle. (For more details on phospholipids, check out the section "Lipids," earlier in this chapter.)

The job of the plasma membrane is to separate the chemical reactions occurring inside the cell from the chemicals outside the cell. Scientists say the plasma membrane is *selectively permeable*, which means it's choosy about what enters and exits the cell.

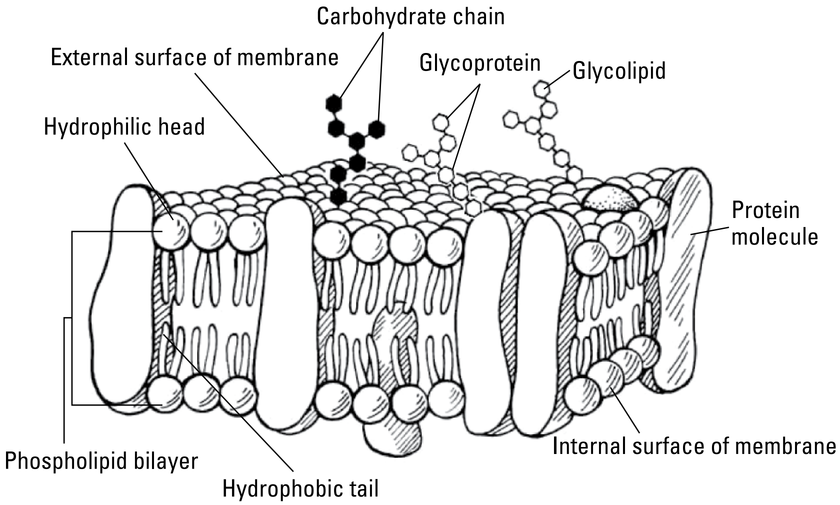

Carbohydrate chain
External surface of membrane
Glycoprotein
Glycolipid
Hydrophilic head
Protein molecule
Phospholipid bilayer
Hydrophobic tail
Internal surface of membrane

FIGURE 2-7: The fluid mosaic model of plasma membranes.

Proteins are also an important part of plasma membranes and help the plasma membrane do its job:

- **Proteins called *receptors* detect signals from the environment of the cell and relay the signal to the inside of the cell.** Scientists call the process of transferring a signal across a membrane *signal transduction*.
- ***Transport proteins* help control which molecules enter and exit the cell.**
  - Transport proteins called *channel proteins* form little tunnels in the membrane that can allow small molecules to pass quickly through the membrane.
  - Another type of transport protein, called *carrier proteins,* pick molecules up on one side of the membrane and then change their shape to deposit the molecules on the other side.

REMEMBER

Scientists refer to the structure of the plasma membrane as the *fluid mosaic model of the plasma membrane.* The membrane is a mosaic because it's made of different components, including phospholipids and proteins. It's fluid because it's flexible and molecules can move within it.

TIP

You can think of the plasma membrane like an international border that controls what enters and leaves the country. The proteins that regulate movement across the membrane are the customs officials.

Just inside the plasma membrane is the *cytoplasm* of the cell, the fluid material that contains all the molecules and structures of the cell. The cytoplasm is a busy place, filled with chemical reactions and moving materials.

REMEMBER

Botanists call everything inside a plant cell, besides the nucleus and the cell wall, the *protoplast*.

TIP

Think of the cytoplasm of a cell like downtown in a busy city. The buildings downtown are like the structures in the cell that specialize for different functions. (Scientists call these structures *organelles*.) The cars speeding through downtown are like the materials that constantly move around in cells.

The library: Storing information in DNA

Just like people store information in libraries, all cells store information in deoxyribonucleic acid. (For the scoop on DNA, see the earlier section "Nucleic acids.") One major difference between prokaryotic and eukaryotic cells, however, is that they package their DNA differently:

- *Eukaryotic cells* separate their DNA from the cytoplasm in the nucleus of the cell by surrounding the DNA with a sphere of membrane called the *nuclear membrane*. Like the plasma membrane, the nuclear membrane is mostly made of phospholipids and proteins. However, the nuclear membrane is actually a double membrane made up of two phospholipid bilayers. Materials and structures can travel in and out of the nucleus through little protein tunnels in the nuclear membrane called *nuclear pores.*
- *Prokaryotic cells* locate their DNA directly within the cytoplasm in a region of the cell called the *nucleoid*.

Factories: Ribosomes

Ribosomes are small structures in cells that help build proteins. Because proteins are very important workers in cells, all cells need ribosomes.

The ribosomes in all types of cells have a very similar structure:

- Ribosomes are made of two types of molecules: a special type of RNA, called *ribosomal RNA* (rRNA), and proteins.

- The rRNA and proteins of ribosomes are twisted together to form two separate pieces: the *large subunit* and the *small subunit*. These subunits are built separately from each other and come together to form a completed ribosome when a cell begins to make a protein.

TIP

Think of ribosomes as little factories where proteins are built.

To make a protein, cells complete two processes:

- **Transcription:** In the nucleus, cells copy the instructions for the protein from the DNA into a new molecule, called *messenger RNA* (mRNA). The mRNA leaves the nucleus and carries the instructions to the ribosomes out in the cytoplasm of the cell.
- **Translation:** Ribosomes organize the mRNA and other molecules that are needed to build proteins and help to put proteins together.

Exploring Plant Cells

Plants, like other eukaryotes, have cells that are highly organized, with lots of compartments for different functions. In addition to the nuclear membrane that walls off the DNA, other membranes form structures called *organelles* that perform specialized tasks for the cell. Plants and animals are both eukaryotes, so their cells have lots in common. In fact, most people would be very surprised to learn how much they have in common with plants!

Almost all eukaryotic cells, including those of plants and animals, contain the following structures (see Figure 2-8):

- Plasma membrane
- Ribosomes
- Nucleus
- Endoplasmic reticulum
- Golgi apparatus (sometimes called *dictyosomes* in plant cells)
- Mitochondria
- Cytoskeleton
- Vesicles, vacuoles, and lysosomes

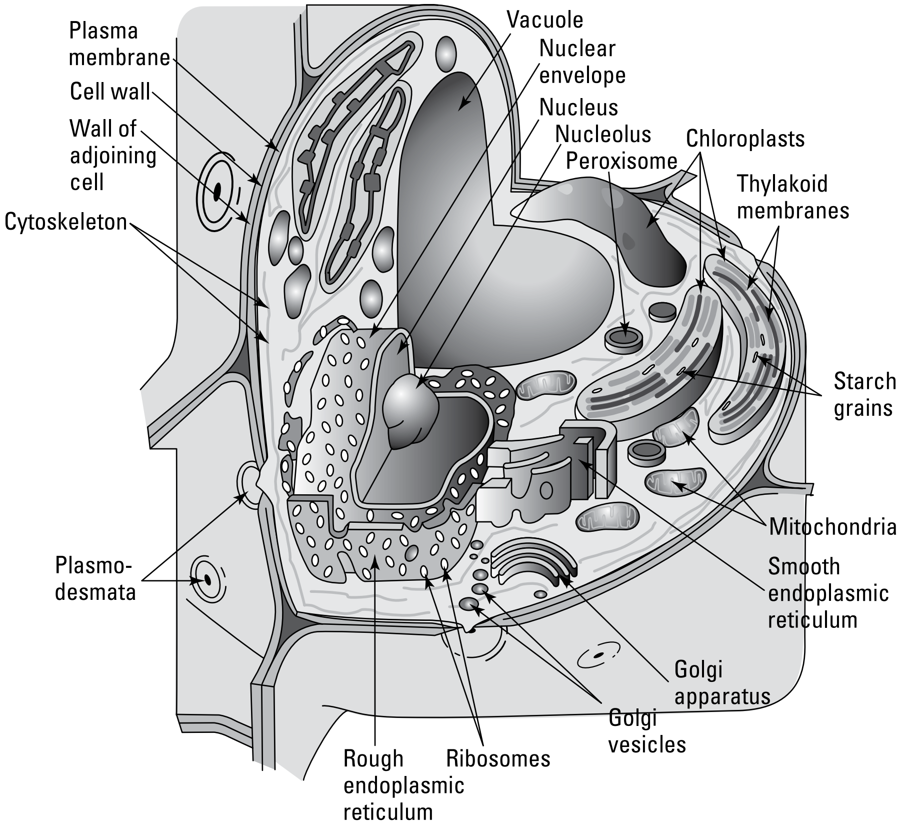

Plasma membrane
Cell wall
Wall of adjoining cell
Cytoskeleton
Plasmo-desmata
Vacuole
Nuclear envelope
Nucleus
Nucleolus
Peroxisome
Chloroplasts
Thylakoid membranes
Starch grains
Mitochondria
Smooth endoplasmic reticulum
Golgi apparatus
Golgi vesicles
Rough endoplasmic reticulum
Ribosomes

FIGURE 2-8: Structures in a typical plant cell.

REMEMBER

In addition, plants have four structures, some of which are found in other eukaryotes, but which are not found in animal cells):

- Cell wall
- Plastids, including chloroplasts
- Large central vacuole
- Plasmodesmata

The following sections cover the cellular structures that are common to all eukaryotes, as well as those that are unique to plants.

Post office: The endomembrane system

The *endomembrane system* is a large network of membranes that helps construct proteins and lipids, packages them up, and then ships them where they need to go. Think of the endomembrane system as the Post Office.

All the components of the endomembrane system are made of membranes that contain phospholipids and proteins:

- The *endoplasmic reticulum,* which scientists call the ER, is a set of folded membranes that begins at the nucleus and extends into the cytoplasm. The ER begins with the outer membrane of the nuclear envelope and then twists back and forth like switchbacks on a steep mountain trail. There are two types of endoplasmic reticulum:
  - *Rough endoplasmic reticulum* (RER) is called "rough" because it is studded with ribosomes. Ribosomes that begin to make a protein that has a special destination, like a particular organelle or membrane, will attach themselves to the rough endoplasmic reticulum while they make the protein. After the protein is made, it is packed in a membrane sphere called a *vesicle*, and then shipped to the Golgi apparatus.
  - *Smooth endoplasmic reticulum* (SER) does not have any attached ribosomes. It makes lipids such as phospholipids for cell membranes.
- The *Golgi apparatus* is a stack of flattened membrane sacs that looks a little bit like a stack of pancakes plus assorted vesicles that are traveling to and from the Golgi. Proteins travel in vesicles to the Golgi from the RER. When proteins arrive at the Golgi, they're modified, marked with chemical tags, and sorted. The proteins leave the Golgi in vesicles and are shipped to their proper destination. Scientists who study plants have their own name for the stack of pancakes part of the Golgi — they call it a *dicytosome*. But dictyosomes and the Golgi apparatus are really pretty much the same thing, with *Golgi apparatus* being the more widely used term.
- *Vesicles* are little spheres of membrane in the cell and come in several types:
  - *Transport vesicles* carry things around the cell. They're like the Priority Mail boxes that you put your letters in. They travel from the ER to the Golgi and then to the plasma membrane or organelles to bring molecules where they need to go.
  - *Lysosomes* are the garbage disposals of the cell. They contain digestive enzymes that can break down molecules, organelles, and even bacterial cells.
  - *Secretory vesicles* bring materials to the plasma membrane so they can be released, or secreted, from the cell.
- *Peroxisomes* are small organelles encircled by a single membrane. Often, they're involved in breaking down lipids like fatty acids. In plant cells, *glyoxisomes*, a special kind of peroxisome, help convert stored oils into molecules that can be easily broken down for energy.

- *Vacuoles* are similar to vesicles in structure — they're basically spheres of membrane, but they have different functions. The majority of space inside most plant cells — up to 95 percent of the cell volume! — is taken up by a *large, central vacuole*. The vacuole is separated by a membrane called the *tonoplast*. Plants use their central vacuole as a place to dump wastes and store materials.

TIP

Think of a plant cell like a water balloon inside a shoe box. The shoe box represents the cell wall that surrounds the plant cell, and the water balloon is the large, central vacuole. The latex of the balloon is like the membrane around the vacuole. All of a plant's cytoplasm is squeezed between this membrane and the cell wall.

Scaffolding and railroad tracks: The cytoskeleton

A network of protein cables called the *cytoskeleton* runs throughout cells, reinforcing their structure and enabling the movement of cells and materials.

Cytoskeletal proteins have three main functions in cells:

- **Scaffolding:** Cytoskeletal proteins underlie membranes, giving them shape and support, much like scaffolding can support a building.
- **Movement of materials within cells:** Cytoskeletal proteins run like railroad tracks through cells, enabling the movement of vesicles and organelles along the proteins.
- **Movement of cells:** Cytoskeletal proteins are found within whip-like cellular extensions called *cilia* and *eukaryotic flagella*. Cells like sperm cells (including the sperm cells made by some plants!) swim by flicking their flagella.

Three types of cytoskeletal proteins reinforce and organize eukaryotic cells:

- **Microfilaments** are made of the protein *actin*. In plant cells, microfilaments are involved in cell division and expansion and act as railroad tracks for vesicles and organelles, helping to circulate the cytoplasm in a process called *cytoplasmic streaming*. In animal cells, microfilaments make muscle cells contract and help pinch cells in two during cell division.
- **Microtubules** are made of the protein *tubulin*. Microtubules are the proteins inside of cilia and flagella. Microtubules also move chromosomes during cell

division, and act as railroad tracks for the movement of vesicles and some organelles. Microtubules help organize the formation of the plant cell wall and thus determine the development of plant shape.

- **Intermediate filaments** are made of various proteins that tend to be strong proteins that help reinforce cellular structures. For example, the protein *lamin* strengthens the nuclear membrane, and the tough protein *keratin* helps reinforce your skin cells and some plant cells, like those in the roots that have to push through the soil.

Solar-powered batteries: Chloroplasts

Most of the food on planet Earth is made by organisms that do *photosynthesis*. During photosynthesis, cells transform light energy from the sun into chemical energy stored in food. Photosynthesis occurs in the cells of plants, algae, and bacteria. The eukaryotic cells of plants and algae contain a special compartment for photosynthesis, a green organelle called a *chloroplast* (see Figure 2-9).

Chloroplasts are green because they contain *chlorophyll*, a green pigment that can absorb sunlight. During photosynthesis, the energy from sunlight is used to combine the atoms from carbon dioxide and water to produce sugars, from which all types of food molecules can be made. (To make proteins, cells also require a source of nitrogen.)

TIP

You can think of chloroplasts as solar-powered batteries because they store energy from the sun as chemical energy in food.

Chloroplasts are bordered by two membranes, an *inner membrane* and an *outer membrane*, both of which are phospholipid bilayers. In addition, they have little sacs of membranes called *thylakoids* stacked up in towers called *grana*. You can see each of these structures in Figure 2-9.

The membranes of the chloroplasts divide them into several different compartments that allow the different reactions of photosynthesis to be separated from each other. (For more details on photosynthesis, see Chapter 5.)

- The *intermembrane space* is between the inner and outer membranes.
- The *stroma* is the fluid-filled space surrounded by the inner membrane.
- The *interior of each thylakoid* is another fluid-filled space.

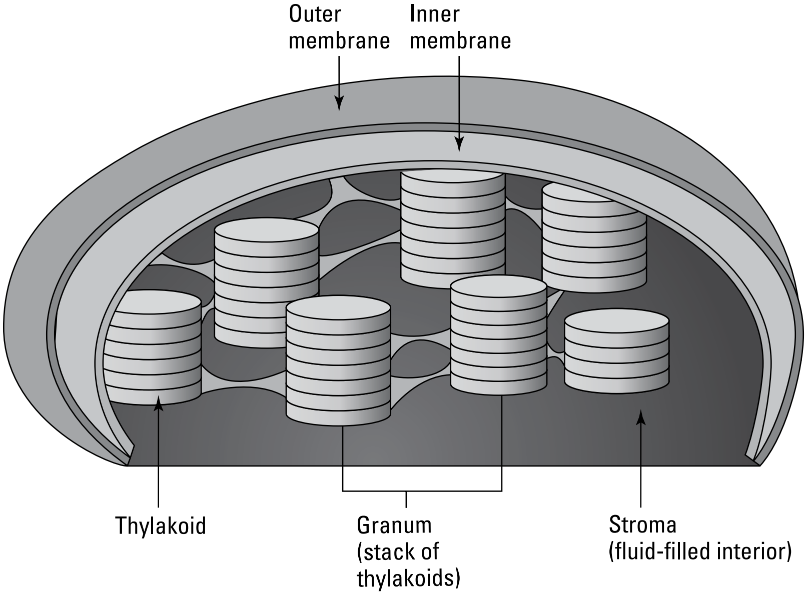


FIGURE 2-9: The chloroplast.

Chloroplasts are a type of *plastid*, self-replicating organelles that are surrounded by a double membrane and that perform important chemical processes in plant cells. The function of chloroplasts is photosynthesis and they're found in the green parts of plants.

Plant structures that specialize for other functions may contain different types of plastids:

- *Proplastids*, also called *eoplasts*, are small colorless plastids that give rise to all the types of plastids. Proplastids are found in seedlings and plant tissues that haven't yet specialized for a certain function.
- *Leucoplasts* are colorless plastids that specialize in the synthesis and storage of important molecules. Three different types of leucoplasts are found in plants:
  - *Amyloplasts* make and store starch. They're typically found in roots and other plant tissues that store starch. For example, potatoes and other tubers are loaded with amyloplasts.
  - *Elaioplasts*, also called oleoplasts, make and store oil. Elaioplasts are found in plant tissues that provide support to developing pollen grains.
  - *Proteinoplasts,* also called proteoplasts or aleuroplasts*,* make and store proteins. Proteinoplasts are found in many seeds, such as peanuts.

- *Chromoplasts* are red, orange, and yellow-colored plastids that contain pigments called *carotenoids*. Chromoplasts are found in flowers, fruits, and leaves that are turning colors in the fall. Chromoplasts can form from chloroplasts and amyloplasts as well as from proplastids.
- *Etioplasts* are pale, yellowish plastids found in plant tissues growing in the dark. When plants are exposed to light, etioplasts develop into chloroplasts.

Powerplants: Mitochondria

Photosynthetic organisms make food, but all organisms break food down in order to obtain matter and energy for growth. In eukaryotes, most of the energy released from food occurs through a process called *cellular respiration* inside an organelle called the *mitochondrion* (see Figure 2-10). During cellular respiration, cells transfer the energy stored in food into a molecule called *adenosine triphosphate* (ATP), which cells can easily use to provide energy for cellular reactions. (For more details on cellular respiration, see Chapter 6.)

WARNING

A very common — but wrong! — idea is that plants have chloroplasts instead of mitochondria. The right idea is that plants have both! Think about it — it wouldn't do plants very much good to make food if they couldn't also break it down! When plants make food, they store matter and energy for later. When they need the matter and energy, they use their mitochondria to break the food down.

Like chloroplasts, mitochondria are surrounded by two membranes: the *outer membrane* and the *inner membrane*. In addition, the inner membrane is folded back and forth, creating folds called *cristae* that are needed during cellular respiration to transfer energy to ATP.

The membranes of the mitochondrion divide it into two different spaces (see Figure 2-10):

- The *intermembrane space* is between the two membranes of the mitochondrion.
- The *matrix* is the fluid-filled space inside of the inner membrane.

TIP

You can think of mitochondria as the power plants of the cell because they transform energy from one form (chemical energy in food) to a form that is more useful for cells (chemical energy in ATP).

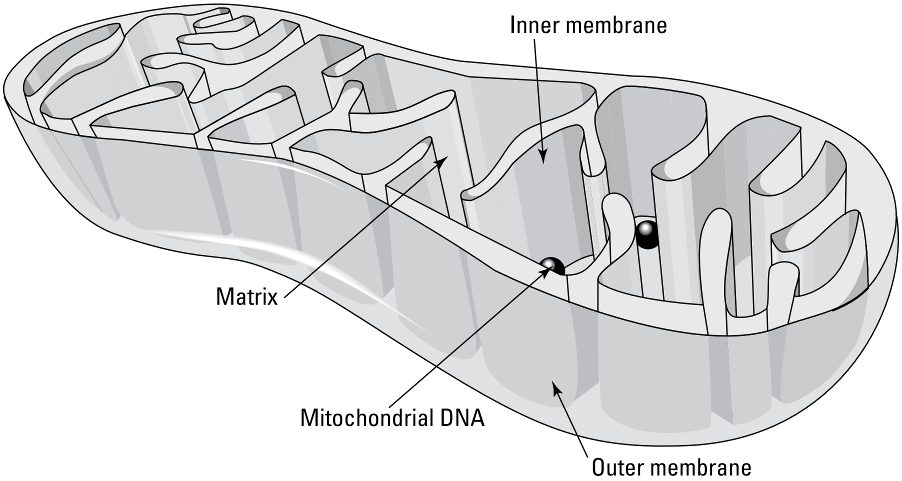


FIGURE 2-10: The mitochondrion.

Rebar and concrete: Cell walls and extracellular matrices

Most cells have additional layers outside of the plasma membrane that provide additional strength to cells and may attach cells together in organisms like plants that are made of more than one cell. Many of these extracellular layers use a strategy that's a lot like putting rebar into concrete in order to make a wall stronger — in cells, long cables of carbohydrates or proteins act like the rebar and a sticky matrix takes the place of the concrete.

Two types of strengthening layers are formed outside of cells:

- *Cell walls* are semi-rigid reinforcing layers that help protect the cell. Many eukaryotes, including plants (see Figure 2-11), fungi, and some protists, make cell walls, as do most bacteria.
- The *extracellular matrix* (ECM) is a flexible layer formed around animal cells. The ECM is made of long proteins, such as *collagen*, embedded in a polysaccharide gel.

The plant cell wall can have several different layers, which you can see in detail in Figure 2-11. Plants make their cell walls from the outside in — outside layers first, followed by the inside layers:

- The *middle lamella* is the outermost layer that helps stick plant cells together. It forms first when plant cells divide. The middle lamella is a thin, flexible layer made mostly of sticky polysaccharides called *pectins*.

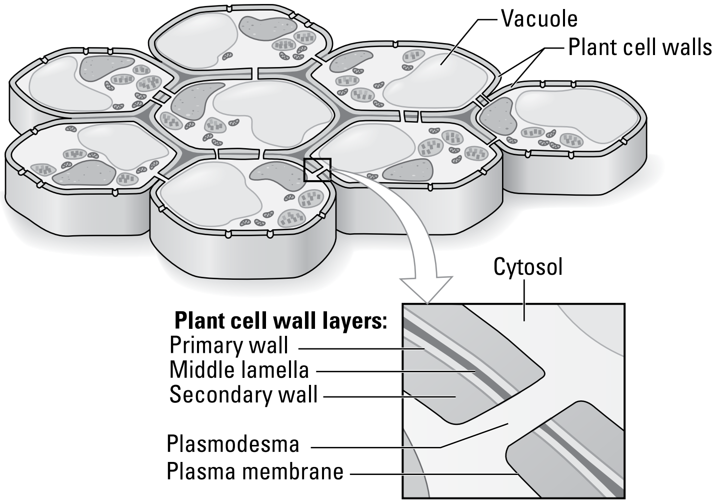


FIGURE 2-11: Plant cell walls and plasmodesmata.

- Plants produce the *primary cell wall* under the middle lamella before and during active growth. The polysaccharide *cellulose* forms strengthening fibers that are embedded in a sticky matrix of pectin and other polysaccharides. The primary cell wall may be thicker than the middle lamella.
- Woody plants produce a *secondary cell wall* and deposit it under the primary cell wall when growth is complete. The secondary cell wall is mostly composed of cellulose and a strong, complex chemical called *lignin.* Lignin is a large strong polymer that acts like superglue over the primary cell wall. Secondary cell walls are the thickest layer of the cell wall.

REMEMBER

Plant cells are protected and stuck together by their cell walls, but they aren't completely walled off from each other. Little tunnels, called *plasmodesmata,* pass through the cell walls, creating connections between neighboring cells. These connections are essential to the movement of materials and communicating molecules between cells.

Combining Cells to Form Tissues

Plants grow as cells divide to produce new cells in areas of the plant called *meristems.* After new cells are produced, they specialize for certain functions, enlarging and changing their structure to match their function. Just as in animals, plant cells are organized into *tissues,* which are collections of cells that work together to perform a function. Tissues are combined together to form *tissue systems.* Tissue systems then make up the *organs* of the plant, which are organized structures such as stems, roots, and leaves that perform specific functions for the whole plant.

Plants have four main types of tissue systems:

- The *meristematic tissue system* contains cells that are actively dividing to produce new plant tissue.
- The *ground tissue system* contains tissues that make up the bulk of the plant, including those that do photosynthesis, support the plant, store food, and repair damage.
- The *vascular tissue system* contains tissues that conduct water, minerals, and sugars throughout the plant.
- The *dermal tissue system* contains tissues that protect the plant and prevent the loss of water from tissues.

Growing with meristems

You've probably heard of *stem cells,* cells in animals that have the ability to become any type of cell in the body. Plants have something similar in their *meristematic tissues*, tissues where cells are actively multiplying to provide new cells for plant growth. New cells produced in the *meristem* are all-purpose cells, just like animal stem cells because they can become any type of plant cell. Cells in the meristem even look generic — they're box-shaped cells with small vacuoles (see Figure 2-12). As the cells enlarge, they begin to *differentiate*, becoming specialized for a certain function. Their appearance changes as they change their structure to match their new function and become recognizable as a certain type of plant cell.

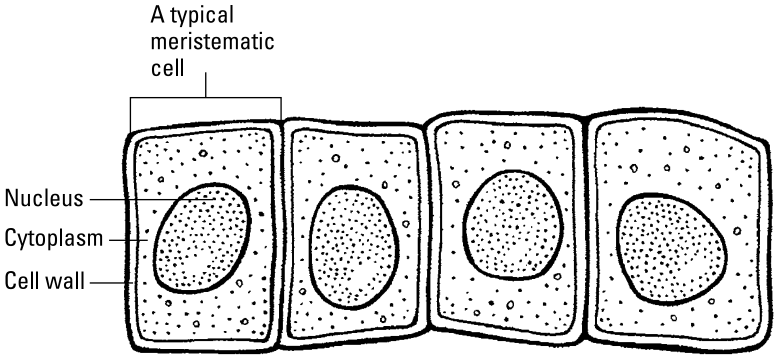


FIGURE 2-12: Meristematic cells.

Most plants have two organ systems:

- The *shoot system,* the parts of the plant that grow above ground. The shoot system can be divided into two types:
  - *Vegetative* shoots support leaves.
  - *Reproductive* shoots support flowers and fruits.
- The *root system*, the underground part of the plant that absorbs water and minerals.

Figure 2-13 shows the locations of meristems in the shoots and roots. Plants have four types of meristems:

- Apical meristems
- Axillary buds
- Lateral meristems
- Intercalary meristems

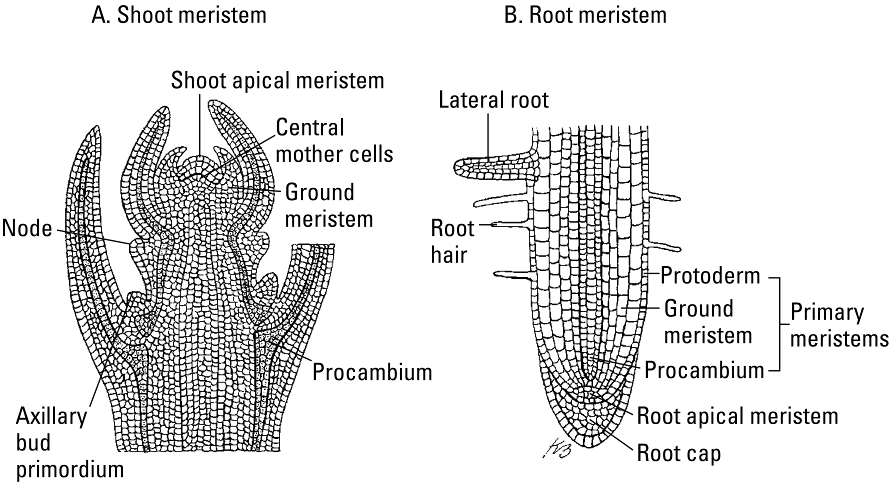

A. Shoot meristem
B. Root meristem
Shoot apical meristem
Central mother cells
Ground meristem
Node
Procambium
Axillary bud primordium
Lateral root
Root hair
Protoderm
Ground meristem
Procambium
Primary meristems
Root apical meristem
Root cap

FIGURE 2-13: Plant meristems.

Apical meristems

Apical meristems are areas of rapidly dividing cells found at the tips of roots and shoots. (*Apical* means from the apex, or from the tip.)

REMEMBER

Plants get taller, and roots get longer, from their tips.

The apical meristems of roots and shoots divide to produce new cells, which then elongate, making roots get longer and shoots get taller. (For more details on plant cell division, head to Chapter 9.)

After cells elongate and differentiate into a particular cell type, they usually can't divide any more due to their rigid cell walls. Meristematic cells, however, continue to divide, enabling growth throughout the life of the plant. The ability to grow throughout life is called *indeterminate growth*. Animals, including people, usually demonstrate *determinate growth,* growth that stops when a structure is fully formed. To understand the differences between these types of growth, compare the height of a tree to that of a person. Trees keep growing taller until they die, whereas people stop getting taller once they reach maturity (which is probably a good thing!).

TIP

If you hung a swing from the branch of a tree when the tree was young, the swing wouldn't rise up into the air as the tree got taller. That's because the tree is getting taller from the top, as the trunk grows longer from its tip.

Axillary buds

As stems elongate, they produce small buds, called *axillary buds,* in the angle between the stem and the petiole of each leaf. Axillary buds may remain dormant for a time, until the apical meristem of the main shoot has grown for a while and moved away from the axillary buds. After the apical meristem is far enough away, the meristems of the axillary buds begin producing new cells, and a branch begins to grow — from its tip, of course, just like any other shoot. Branches are just shoots that emerge from points, called *nodes,* along the main shoot. (I discuss the plant hormones that control the dormancy of the axillary buds in Chapter 8.)

TIP

If you've ever pinched off the tip of a plant in order to encourage more branching, the reason it worked was because you helped wake up those axillary buds by removing the apical meristem of the main shoot.

Lateral meristems

Lateral meristems are thin cylinders of meristematic tissue that form in mature regions of shoots in roots in many plants, especially those that produce woody tissue. Lateral meristems divide to produce *secondary growth,* growth that increases the diameter of a shoot or root.

TIP

If you tied a ribbon around the trunk of a young tree, the ribbon would eventually break as the tree got thicker. Lateral meristems produce the cells that make the tree get thicker.

Plants have two types of lateral meristems:

- The *vascular cambium* produces new vascular tissue.
- The *cork cambium* divides to produce *cork,* a tissue found in the outer bark of woody plants.

If you think of the vascular cambium as a straw of tissue inserted into a stem or root, then the cork cambium is a slightly larger straw that surrounds the first.

Intercalary meristems

Intercalary meristems are regions of meristematic tissue that occur at intervals along the stems of grasses and related plants. When cells of the intercalary meristem divide, they add new cells to the stem, increasing its length.

TIP

You can mow your grass, chopping off all the plants' apical meristems. For plants that don't have intercalary meristems, the loss of the apical meristem greatly impacts their ability to grow taller. Not so for grasses! When you cut off their apical meristems, they continue to get longer from the division of their intercalary meristems. The result? You have to mow again! This trait gives grasses a survival advantage in environments with grazing mammals, wildfires, or lawn mowers. (For more on how advantageous traits spread through populations, check out Chapter 11).

Building plant bodies with ground tissue

Most of the primary growth of plants consists of ground tissue. Because it occurs everywhere in plants, it's often interspersed with other tissues. Figure 2-14 shows the three types of simple tissues that make up the ground tissue system:

- Parenchyma
- Collenchyma
- Sclerenchyma

REMEMBER

Simple tissues typically consist of only one type of cell, whereas *complex tissues* contain more than one type of cell.

Parenchyma

Parenchyma cells are your general, all-purpose type of plant cell. They're the most abundant type of cell in a plant and can perform several different functions, such as metabolism and storage of different materials. For example, parenchyma cells in leaves are full of chloroplasts so they can do lots of photosynthesis, whereas parenchyma cells in a storage organ, like a potato tuber, store lots of starch grains in amyloplasts. Parenchyma cells may also contain crystals, oils, or other types of plastids. *Secretory cells* are cells derived from parenchyma cells. These cells produce special substances inside the plant body and then store the materials in channels before releasing them to the outside of the cell, or even to the outside of the plant body.

Parenchyma has two key characteristics that can help you distinguish it from other tissues:

- **Thin walls:** Parenchyma cells have a primary cell wall of cellulose and remain relatively flexible. Depending on how they're pushed together in a tissue, they can have slightly different shapes, but they're often block shaped or rounded.
- **Alive at maturity:** Parenchyma cells remain alive and still have the potential to divide when they're fully developed. They can live for a really long time — up to 100 years in some cactus plants!

TECHNICAL STUFF

Parenchyma cells that are full of chloroplasts are called *chlorenchyma*. Parenchyma cells with lots of interconnected air spaces, like those in aquatic plants, are called *aerenchyma*.

Collenchyma

Collenchyma cells are very similar to parenchyma cells, with the exception of having thickened cell walls. The thickened yet flexible cell walls enable collenchyma tissue to support both growing and mature plant organs.

TIP

If you want to get a real feel for collenchyma, eat a stalk of celery. The long flexible strings that tend to get stuck in your teeth contain collenchyma. They're strong, yet flexible, providing bendable support to the celery stalk.

Collenchyma has three key characteristics that can help you distinguish it from other tissues:

- **Thickened cell walls:** The cell walls of collenchyma cells are thickened unevenly and may be thickest at the corners (refer to Figure 2-14). The cell walls of collenchyma are primary cell walls, so they don't contain lignin, which helps keep the tissue from becoming rigid.

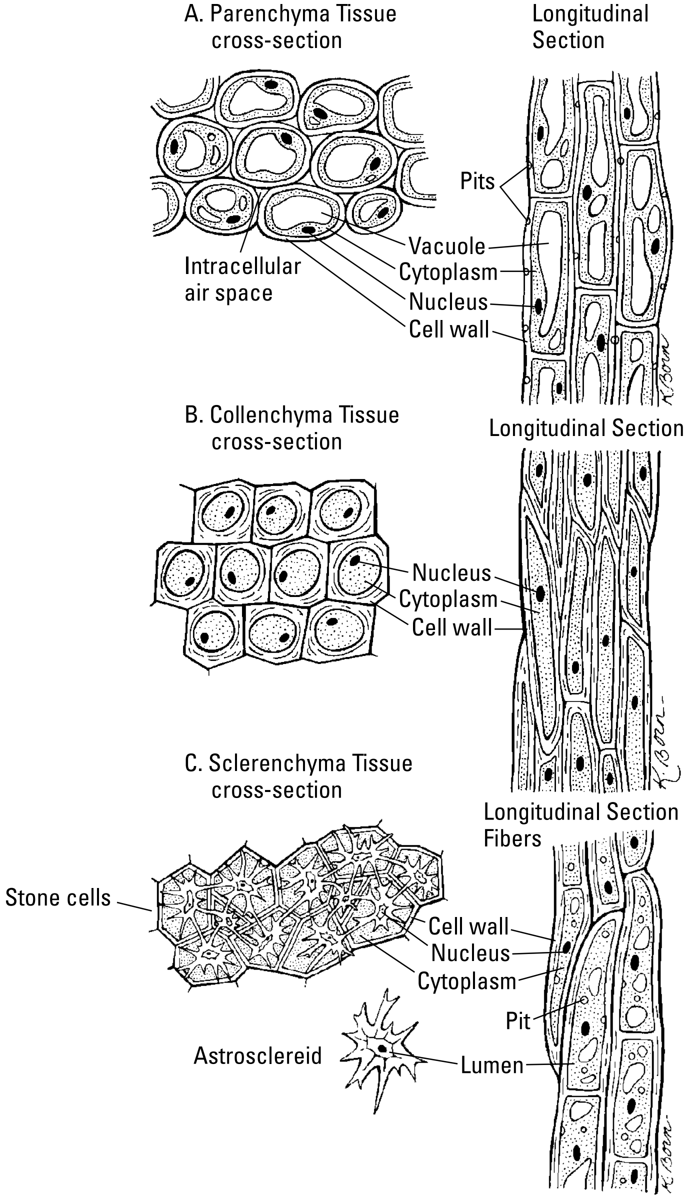

A. Parenchyma Tissue
cross-section
Longitudinal
Section
Pits
Vacuole
Cytoplasm
Nucleus
Cell wall
Intracellular
air space
B. Collenchyma Tissue
cross-section
Longitudinal Section
Nucleus
Cytoplasm
Cell wall
C. Sclerenchyma Tissue
cross-section
Longitudinal Section
Fibers
Stone cells
Cell wall
Nucleus
Cytoplasm
Pit
Astrosclereid
Lumen
K.Born

FIGURE 2-14: Simple plant tissues.

- **Location just under the epidermis:** Parenchyma tissues may be located throughout the plant, but collenchyma is typically found just under the epidermis, which is the outermost layer of cells on the plant.
- **Alive at maturity:** Like parenchyma cells, collenchyma cells are functioning cells that can live a long time.

Sclerenchyma

Sclerenchyma cells have thick cell walls that contain lignin, which makes them very tough and supportive. Sclerenchyma protects plant organs from damage due to stress, such as bending and stretching.

TIP

If you want to check out some sclerenchyma, you could eat a pear. The gritty texture of a pear is due to a type of sclerenchyma cell called *stone cells* that are embedded in the fruit. Or try testing the hardness of a peach or plum pit — the outer layer of the pit is hardened with lots of sclerenchyma cells.

Sclerenchyma has three key characteristics that can help you distinguish it from other tissues:

- **Thick cell walls:** Sclerenchyma cells have thick secondary cell walls that contain lignin and are laid down inside the primary cell wall. To see how thick the cell walls can get, see the stone cells in Figure 2-14.
- **Dead at maturity:** Sclerenchyma cells die after they become fully mature. The cytoplasm breaks down, leaving just the cell wall behind.
- **Location throughout plant:** Sclerenchyma can be located in many different tissues (unlike collenchyma, which is typically located just under the epidermis).

TECHNICAL STUFF

Sclerenchyma cells are divided into two groups: *sclereids* and *fibers*. Sclereids are shorter than fibers — usually about as long as they are wide. Two types of sclereids, stone cells and astrosclereids, are shown in Figure 2-14. Fibers, which are also shown in Figure 2-14, are much longer than they are wide and are tapered at the ends. Fibers usually occur in strands, with the individual fibers overlapping slightly.

FASHIONABLE FIBERS

Do you have any clothing or household items made out of linen? If you do, then you know firsthand one of the uses that people have found for sclerenchyma. Linen is made from the flax plant (*Linum usitatissimum).* Sclerenchyma fibers are removed from the stem, spun into thread, and then woven into linen cloth. Before cotton was mass produced during the Industrial Revolution in the 19th century, linen was the fabric of choice for societies from the ancient Egyptians to the British colonials. Linen was such an important fabric that today people use the phrase *fine linens* to refer to any high-quality house fabrics. You can read more about linen and other textiles made from plants in Chapter 18.

Protecting plants with dermal tissue

Dermal tissues cover plant surfaces or create barriers that protect the plant. Scientists include three tissues in the dermal tissue system:

- Epidermis
- Endodermis
- Periderm

Epidermis

REMEMBER

Plants are covered by a single layer of cells, called the *epidermis*, that separates the inside of the plant from its environment. The epidermis is made mostly of parenchyma-like cells that are alive at maturity.

The epidermis has three primary functions:

- **Prevent water loss:** Most epidermal cells secrete a waxy material called *cutin,* which forms a waxy layer called the *cuticle* on the outside of the plant. The cuticle provides waterproofing to the plant tissues so that their water doesn't just evaporate into the air. Epidermal cells are also packed tightly together with very little space between the cells so that water can't evaporate out from between them.

  The epidermis of the shoot system may also produce little hair-like projections called *trichomes*. Trichomes have many functions depending on the plant that produces them. In some plants, trichomes help prevent water loss by creating a barrier to air movement along the surface of the plant that could speed up evaporation. Plants may also use trichomes for defense and seed dispersal. Some trichomes are glandular and contain secretory cells that produce materials like oils.
- **Protect plant from fungi and other attackers:** The waxy cuticle and closely spaced cells of the epidermis help prevent fungi, bacteria, and insects from being able to access the plant tissues. The wax makes the cells harder to penetrate, and the tightly packed cells prevent attackers from slipping into the interior of the plant through gaps between the cells.
- **Allow plant to exchange materials with the environment:** Plants have to strike a balance between preventing water loss and being able to get what they need from their surroundings. In order to live and grow, plants need to be able to move materials through the epidermis:

- *Plants exchange gas with the atmosphere:* Plants need to take carbon dioxide (CO_2) from the air in order to do photosynthesis (see Chapter 5), and they release oxygen gas (O_2) as waste. The waxy cuticle is great for stopping water loss to the air, but it also prevents gas exchange. So, plants need openings in the epidermis (sort of like you need nostrils in your nose). These openings are called *stomata* or *stomates* (singular = *stoma*). Plants control whether their stomata are open or shut with special cells called guard cells.
- *Plants absorb water and minerals from the soil:* Roots absorb water and minerals from the soil through their surface cells. To help create more surface for water absorption, root epidermis produces little projections called *root hairs*. Plants like orchids that grow up in the trees produce aerial roots covered with *velamen*, an especially absorptive type of epidermis. Velamen enables the plants to capture water and minerals from the air.

Endodermis

The endodermis is a layer of cells between the cortex and vascular tissue in roots, as well as some stems and leaves. The endodermis is very important to the overall water balance of plants because it helps regulate the uptake of water from the soil and helps prevent the loss of water from plants.

Periderm

REMEMBER

The periderm is the outermost tissue in woody plants, forming the outer bark. Periderm is a complex tissue, consisting mostly of cork cells and parenchyma cells:

- **The cork cells of the periderm help protect the stem.** The stems of woody plants get thicker as the cork cambium and vascular cambium begin to divide. As the stems get thicker, the original epidermis cracks and falls off. A new protective layer forms from the box-shaped *cork cells* produced by the cork cambium. The cork cells produce a waxy substance called *suberin,* which helps protect the stem of the plant from water loss and attack from fungi and other pests. Once the cork cells reach maturity, they die.
- **The parenchyma cells of the periderm allow gas exchange with the environment.** The cork cambium also produces clusters of parenchyma cells, forming pockets of tissue called *lenticels*. The parenchyma cells aren't waxed, so they can still exchange gasses like carbon dioxide (CO_2) and oxygen (O_2) with the environment.

TIP

You can see lenticels on the surfaces of some darker woods, like horse chestnut, birch, and cherry. Lenticels look like little eye-shaped lighter areas on the wood.

Transporting materials with vascular tissue

The vascular tissue system acts as the plant's plumbing, moving water and sugars throughout the plant. The vascular tissue system contains two types of complex tissues:

- **Xylem:** Transports water and minerals throughout the plant body.
- **Phloem:** Transports sugars throughout the plant body.

Xylem

REMEMBER

Xylem is like the plumbing system of a plant, transporting water and minerals vertically through the plant from the roots to the leaves.

Xylem is a complex tissue consisting of several cell types, including the distinctive tracheids and vessel elements shown in Figure 2-15. In addition to transporting water and minerals, the secondary cell walls in xylem helps strengthen and support plant stems.

Xylem contains as many as five types of cells:

- **Tracheids** are long, thin cells with pointed ends that conduct water vertically. Tracheids line up in columns like pipes by overlapping their tapered ends. Tracheids die when they reach maturity, so water is conducted through the tubes made up of tracheid cell walls.

  Wherever two ends join, small holes in the cell wall called *pits* line up to allow water to flow from one tracheid to another. Pits always occur in pairs so that a pair of pits lines up on either side of the middle *lamella,* or center layer, of the cell wall. (See Chapter 2 for more details on plant cell walls.)
- *Vessel elements* are barrel-shaped cells with open ends that conduct water vertically. Like tracheids, vessel elements line up end to end forming columns, called *vessels,* that conduct water. Some vessel elements have completely open ends, while others have narrow strips of cell wall material that partially cover the ends. Vessel elements, like tracheids, die when they reach maturity.
- *Ray cells* are long-lived parenchyma cells that extend laterally like the spokes of a wheel from the center of a woody stem out toward the exterior of the stem. Ray cells are alive at maturity, and they transport materials horizontally from the center of a stem toward the exterior.
- *Xylem fibers* are long, thin sclerenchyma cells that run parallel to the vessel elements. Xylem fibers help strengthen and support the xylem.

- *Xylem parenchyma cells* are living parenchyma cells distributed among the vessels and tracheids. Xylem parenchyma cells store water and nutrients.

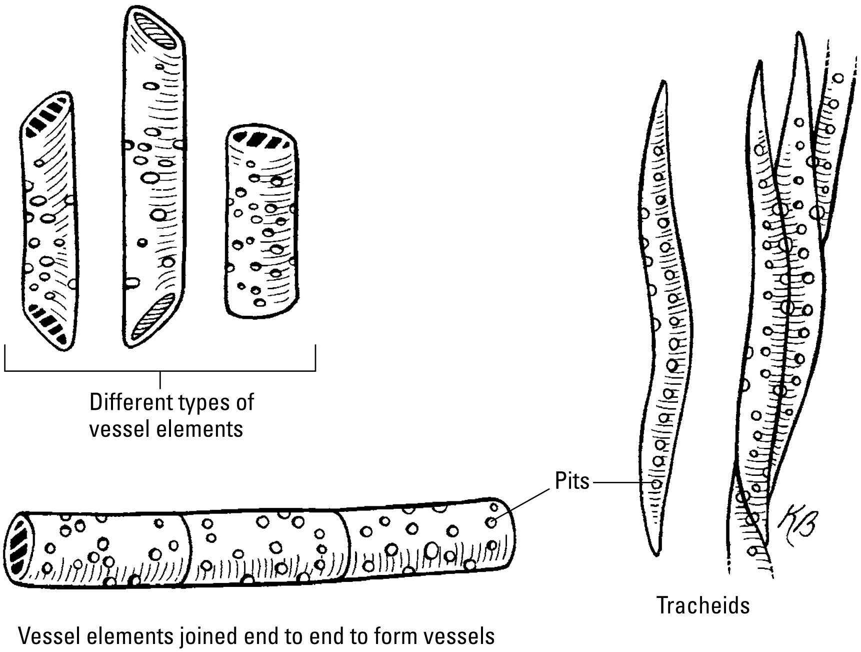

Different types of vessel elements
Pits
Vessel elements joined end to end to form vessels
Tracheids
KB

FIGURE 2-15: Types of water conducting cells.

TECHNICAL STUFF

When scientists look at plant fossils, they find evidence of tracheids in the oldest plant fossils, with vessels found in more recent fossils. Because of this evidence, scientists believe that tracheids evolved first and vessels evolved later. Today, tracheids are found more commonly in gymnosperms, including conifers, while vessels and tracheids are found in flowering plants. The trend in vessel elements over time seems to move away from a tracheidlike shape of thin and tapered, to a more open, barrel-like shape. The ends of vessel elements also seem to evolve from partially covered to completely open.

Phloem

REMEMBER

Phloem acts like the circulatory system of a plant, bringing sugar from the leaves to all parts of the plant body. Phloem is a complex, living tissue at maturity that contains several types of cells, including the two most common types, sieve tube elements and companion cells, shown in Figure 2-16. Like the xylem, phloem also contains rays, fibers, and parenchyma cells.

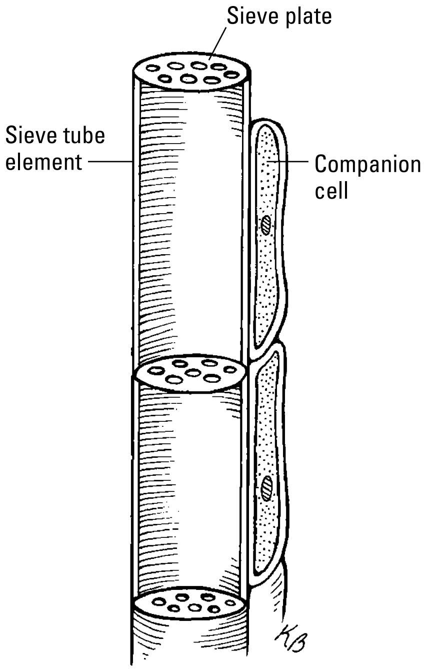


FIGURE 2-16: Components of phloem.

Phloem contains as many as five types of cells:

- **Sieve tube elements** are long, straw-like cells that link themselves end to end to form *sieve tubes* that conduct sugar throughout the plant. The ends of sieve tube elements have lots of holes in the cell wall, forming a perforated plate called a *sieve plate* that allows the sugar solution to pass from one cell to the next in the sieve tube. Sieve tube elements are alive at maturity, but they have no nucleus of their own, relying instead upon their adjacent companion cells.
- **Companion cells** are living, nucleated cells that occur adjacent to sieve tube elements. Companion cells regulate the sieve tube elements and help them maintain themselves.
- **Phloem ray cells** extend laterally through stems allowing horizontal transport of materials. Phloem rays and xylem rays form from the same cells and are very similar in structure and function.
- **Phloem fibers** are long, thin sclerenchyma cells that run parallel to the sieve tube elements. Phloem fibers help strengthen and support the phloem.
- **Phloem parenchyma cells** are living parenchyma cells located between the sieve tubes. These cells store water and food.

IN THIS CHAPTER

- Defining vegetative plant organs
- Distinguishing between primary and secondary growth
- Examining the structure and function of stems, roots, and leaves

Chapter 3

Vegetative Structures: Stems, Roots, and Leaves

Plants produce vegetative and reproductive organs. Vegetative organs, such as stems, roots, and leaves, help plants make and use food, obtain water and minerals, and store resources like food and water. Differences in the structure of stems and roots occur between two major groups of flowering plants, the monocots and the dicots, and between herbaceous plants that show only primary growth and woody plants that show secondary growth.

In this chapter, I present the basic structure and function of vegetative plant organs and introduce you to the diversity of these organs among different plant groups.

Getting Organized into Plant Organs

You're no doubt aware of your own organs like your heart, kidneys, or lungs. You may not have thought of plants as having organs, too, but they do!

REMEMBER

Plant *organs* are groups of several types of tissues that together perform a particular function.

Vegetative organs — stems, roots, and leaves — make and use food, absorb water and minerals, transport materials throughout the plant, and store food. Reproductive organs, such as flowers and cones, participate in sexual reproduction. (For more info on reproductive organs, see Chapter 4. For the details on sexual reproduction, see Chapter 9.)

Within the plant body, three major organs perform all the vegetative functions necessary for life:

- **Stems** support the leaves and transport water, minerals, and sugars throughout the plant.
- **Roots** anchor the plant in the ground and absorb water and minerals from the soil.
- **Leaves** make sugars through the process of photosynthesis (see Chapter 5).

Getting Taller with Stems

Anytime you use something made of wood, you're using something made from the stem of a plant. *Stems* are linear structures with attached leaves that provide support and transport of water and nutrients to the plant body. Most stems grow upward, helping to raise plant structures, such as leaves, off the ground. Some plants also use their stems for photosynthesis or for food and water storage.

You can see the parts and organization of stems fairly easily on a woody stem, like the one shown in Figure 3-1:

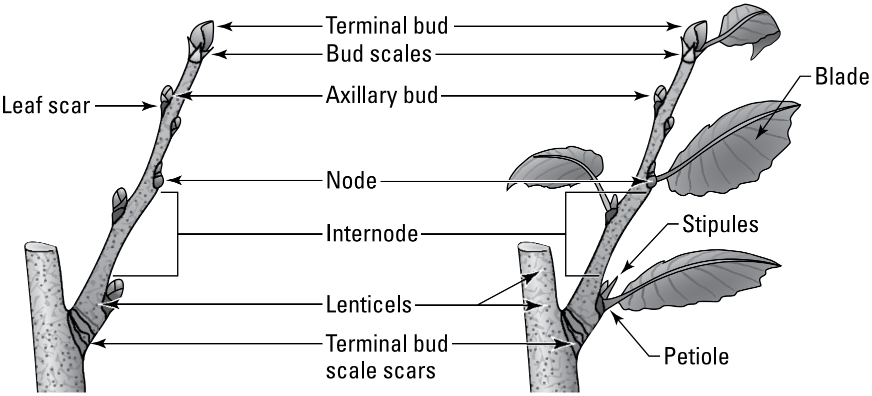


FIGURE 3-1: External anatomy of a woody stem.

- **The apical meristem is located in a bud, called a *terminal bud,* at the tip of the stem.** New growth in length occurs because of cell division in the apical meristem. Along with the apical meristem, terminal buds may contain *leaf primordia,* which are fully formed, tiny embryo leaves that are ready to expand and grow when the bud opens. Buds are usually protected by hard, leaf-like structures called *bud scales.* When the terminal bud begins to grow, the bud scales fall off, leaving a ring of scars that go 360 degrees all around the stem.

  TIP

  For deciduous trees growing in temperate climates, you can tell how many years a woody branch has been growing by counting the number of rings of bud scale scars.
- **Leaves grow from the stem at *nodes.*** On branches from plants that drop their leaves, called *deciduous plants, leaf scars* show where the leaves used to be attached. If you look closely at leaf scars, you can see little circular marks within them that show where the vascular tissue from the stem ran out into the leaf. These vascular scars are called *bundle scars* because they mark the places where bundles of vascular tissue were located. The spaces between nodes on the stem are called *internodes.*
- **Meristems are also located in *axillary buds* that are tucked in the angles, or *axils,* between the leaves and the stem.** When an axillary bud begins to grow, its meristems function just like the apical meristem producing new growth through cell division. Axillary buds may grow into new branches, or they may produce flowers. Just like terminal buds, axillary buds are usually protected by bud scales.

All plants grow by getting taller as the apical meristem produces new cells at the tip of the stem. Additionally, the stems of some plants that grow for more than one year will grow thicker over time. So, two types of growth occur in stems:

- **Primary growth increases the length of the stem.** Primary growth results from cell division in apical meristems and builds *herbaceous stems,* which are nonwoody stems. (For the scoop on apical meristems, see Chapter 2.)
- **Secondary growth increases the width of the stem.** Secondary growth results from cell division of the vascular cambium and builds *woody stems,* stems that contain secondary xylem tissue. (For more info on the vascular cambium and xylem tissue, check out Chapter 2.)

Primary growth

When the cells in the apical meristem divide, they produce primary meristem tissues — the protoderm, ground meristem, and procambium — that will form all the primary tissues of the stem. (For the fundamentals on meristems and tissues, see Chapter 2.)

The organization of primary tissues inside stems differs somewhat among plant groups, but most flowering plants and conifers organize their vascular tissues into *vascular bundles*, groups of pipe-like tissues that run longitudinally through the roots, stems, and leaves.

In primary stems, vascular bundles have three components (check out Figures 3-2 and 3-3 to see vascular bundles close-up):

- A layer of thick-walled cells, such as sclerenchyma and collenchyma, that surround the bundle, protecting the bundle and supporting the stem.
- A cluster of phloem cells, located on the side of the bundle closest to the outside of the stem. These cells transport food.
- A cluster of xylem cells, located on the side of the bundle closest to the inside of the stem. These cells transport water and minerals.

Botanists divide flowering plants into two major groups — *monocots* and *dicots* — based on several differences in their structures, including differences in stem organization. Monocots include plants such as the grasses, lilies, and palm trees. Dicots include roses, beans, and broadleaf trees. This chapter presents the differences in vegetative structures of monocots and dicots. Chapter 4 covers reproductive differences.

Monocot stems

Most monocots grow only by primary growth, remaining herbaceous throughout their lives. But some monocots, such as palms, have very fibrous leaf bases wrapped around their stems so that they appear to be woody. Figure 3-2 shows the internal anatomy of a monocot stem.

REMEMBER

The vascular bundles of monocots form in a spiral arrangement around the stem.

Moving from the outside to the inside, monocot stems, like the one in Figure 3-2, are made up of epidermis and then ground tissue with vascular bundles that appear to be scattered randomly around the stem.

Dicot stems

Many wildflowers and crop vegetables that are dicots grow only by primary growth. Dicots that grow into shrubs and trees begin growing with primary growth and then grow by secondary growth.

Dicot stems, like the one in Figure 3-3, are surrounded by a sheath of epidermal tissue. The rest of the stem, with the exception of the vascular tissue, is made up of ground tissue.

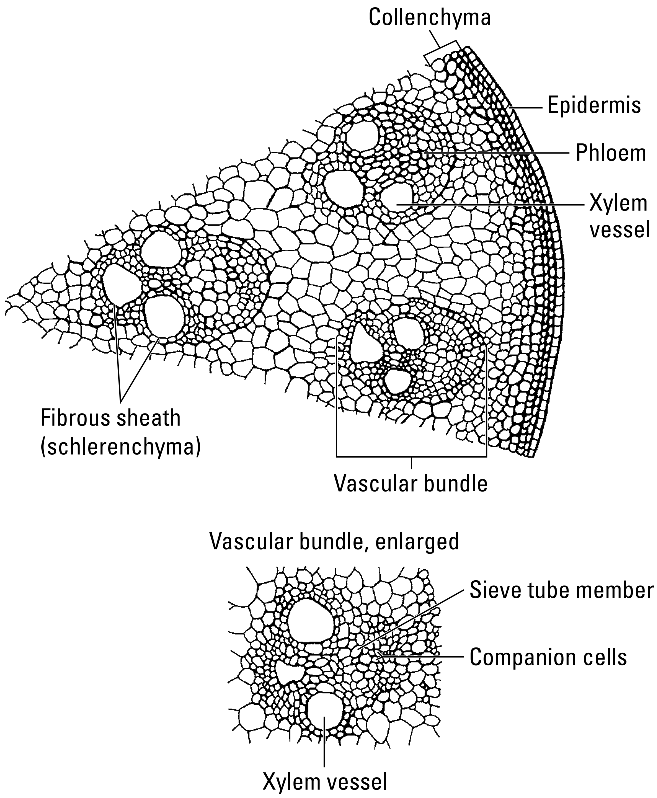

Collenchyma
Epidermis
Phloem
Xylem vessel
Fibrous sheath (schlerenchyma)
Vascular bundle
Vascular bundle, enlarged
Sieve tube member
Companion cells
Xylem vessel

FIGURE 3-2: Internal anatomy of a monocot stem.

In young dicot stems, ground tissue is organized into two layers of tissue:

- The *cortex* is made of several layers of parenchyma cells and is located between the epidermis and the vascular tissue.
- The *pith* is the group of parenchyma cells in the center of the stem.

REMEMBER

Dicots arrange the vascular bundles in a ring around the stem. Moving from the outside to the inside, primary dicot stems, like the one in Figure 3-3, are made up of epidermis, ground tissue (cortex), vascular bundles, and ground tissue (pith).

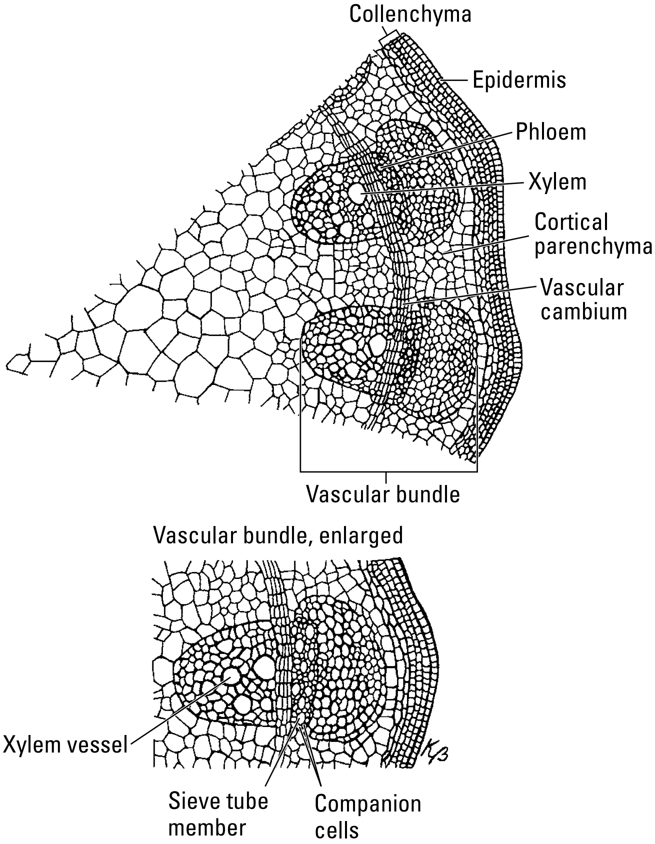

Collenchyma
Epidermis
Phloem
Xylem
Cortical parenchyma
Vascular cambium
Vascular bundle
Vascular bundle, enlarged
Xylem vessel
Sieve tube member
Companion cells

FIGURE 3-3: Internal anatomy of an herbaceous dicot stem.

Secondary growth

Whether or not a plant performs secondary growth depends largely upon how long the plant lives:

- *Annual plants,* which complete their entire life cycle from germination to death within one year, don't do secondary growth.
- *Perennial plants,* which live multiple years, do secondary growth.

Another factor that determines growth pattern is the type of plant. Monocots don't do true secondary growth, while gymnosperms (see Chapter 15) and dicots both do secondary growth in a similar way. Figure 3-4, which shows the secondary growth of a dicot stem, shows an example of how these two groups grow.

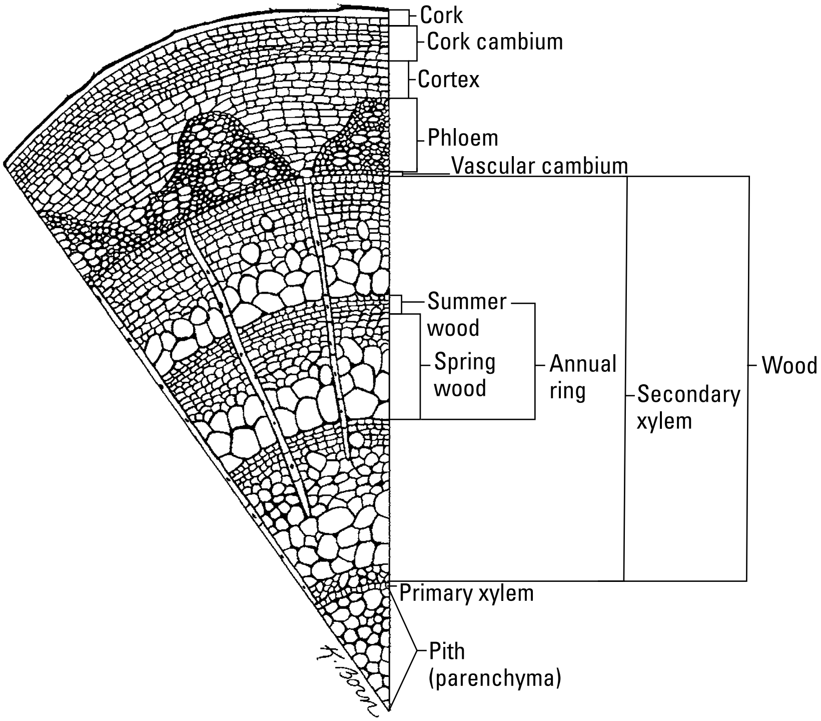

Cork
Cork cambium
Cortex
Phloem
Vascular cambium
Summer wood
Spring wood
Annual ring
Secondary xylem
Wood
Primary xylem
Pith (parenchyma)
K. Born

FIGURE 3-4: Internal anatomy of a woody dicot stem.

Two rings of meristematic tissue, called *lateral cambia*, produce the new cells that make up secondary growth:

- The *vascular cambium* makes new vascular tissue, called *secondary xylem* and *secondary phloem*. The cells of the vascular cambium are between the xylem and phloem in the vascular bundles of dicots and conifers. So, as the vascular cambium makes new cells, they push the secondary xylem toward the inside of the stem and secondary phloem toward the outside of the stem.
- The *cork cambium* (also called *phellogen)* produces ground tissue (also called *phelloderm)* toward the inside of the stem and *cork cells* (also called *phellem*) toward the outside of the stem. Cork cells help protect woody stems because they're impregnated with a waxy substance called *suberin,* which makes them waterproof and resistant to fire damage, infection, and insect attack. These cork cells eventually replace the epidermal cells that break away as the stem thickens. *Lenticels* are spongy areas within the cork that allow gas exchange.

REMEMBER

The bark of a tree consists of all the cells from the vascular cambium to the outside of the stem, so it includes the secondary phloem, parenchyma, and cork cells. The outer bark, which consists of just the cork cambium and the cells it produces (cork and parenchyma), is called the *periderm*.

The vascular cambium and cork cambium both develop from primary tissue in the stem as a stem enters into secondary growth:

- The **vascular cambium** forms from cells between the xylem and phloem within the vascular bundles and from parenchyma cells in the spaces between the bundles. These cells develop into meristematic cells that join up with each other to form a ring of cells just one cell thick within the stem.
- The **cork cambium** usually forms from a ring of cells within the cortex of the stem. These cells develop into meristematic cells that form the ring of cork cambium within the stem.

As the stem grows over time, new cells from the vascular cambium cause the vascular bundles to enlarge, until they eventually merge together to form a central ring of vascular tissue within the stem.

TIP

Moving from the outside of the stem to the inside, woody dicot stems, like the one in Figure 3-4, are made up of periderm, including the cork cambium, then ground tissue (cortex), primary phloem, secondary phloem, vascular cambium, secondary xylem, primary xylem, and ground tissue (pith).

As a woody stem grows year after year, the vascular cambium continues to add new vascular tissue. The secondary phloem cells get pushed into the bark of the stem. These cells are fairly fragile and tend to get crushed over time, so the amount of secondary phloem in a woody stem stays relatively constant. However, the secondary xylem is very strong and gets added to the stem in layers, year after year.

THE CORK IS OUT OF THE BOTTLE

Wine bottles today sometimes come with screw caps or plastic corks, but the original wine corks are made of — well, cork! Trees called cork oaks, *Quercus suber,* have a well-developed cork cambium and produce large amounts of thick, spongy bark. People harvest this cork sustainably, by giving the trees nine to ten years to recover in between harvests. Cork forests are the home to many species of plants and animals and also provide the economic livelihood for groups of people in the Mediterranean.

In temperate climates, the layers of secondary xylem form tree rings:

- Xylem vessels produced during spring and summer, when growth is most favorable, have a large cell diameter. The wood in this area appears lighter in color and is called *spring wood*.
- Xylem vessels produced during late summer and fall, when growth is less favorable, have a smaller cell diameter. The wood in this area appears darker in color and is called *summer wood*.

Because each ring represents a year's growth, you can count the rings in a tree to determine how old it is. Botanists and foresters use a tool called an *increment borer* to cut a core of wood out of a tree so that they can count the rings. An increment borer is like a sharp metal straw that can be twisted into the trunk of a tree, cutting the wood as it goes in. When you pull the borer back, it removes a cylinder of wood that shows the tree rings. In addition to telling a tree's age, the core can also tell you which years were good growing years and which years had hazards such as fires. In general, the larger the xylem vessels, the better the year.

Wood is all the tissue inside a woody stem from the vascular cambium to the center of the stem, which is mostly made up of secondary xylem with a small amount of primary xylem. Wood can be divided into two categories, based on whether it's still transporting water and minerals:

- *Sapwood* has functioning vessels and tracheids. Sapwood makes up the outer part of secondary xylem.
- *Heartwood* no longer transports water and minerals, but it still provides tremendous support to the stem. Heartwood is impregnated with chemicals called resins and tannins that help prevent infection.

REMEMBER

Vascular rays are cells that are arranged horizontally within the wood. They help move materials laterally in stems, from inside to outside.

Specialized stems

You can easily recognize a plant stem when it grows upward, but would you recognize a stem that was growing flat along the ground, or even under the ground?

SENIOR CITIZENS OF THE PLANT WORLD

Small, twisted pine trees cling to the rocks on the side of a mountain in the Great Basin National Park in Baker, Nevada, the last of the trees as you climb up to 7,000 feet. It's amazing that these trees can survive the harsh conditions at these high elevations — the cold, the short growing season, and the biting winds. But the trees not only survive, they grow. And just like other woody species, they add a ring of vascular tissue to their stems for every year they're alive.

In 1964, a scientist was given permission to study some of the bristlecone pines growing in the park, including permission to cut down one tree so that he could learn about the history of the tree from looking at its rings. The scientist chose a tree that the local mountaineers called Prometheus. When scientists counted Prometheus' rings, they found out that the tree was about 4,900 years old! Bristlecone pines that have been studied since the 1960s have confirmed that these trees live to a very ripe old age — one in the White Mountains of California is 5,065 years old — making these the oldest known living trees. And, an interesting insight is that the harsh life at high elevations seems to help bristlecone pines achieve their long life. Bristle cone pines that grow at lower elevations in more pleasant conditions don't live nearly as long.

Some plants modify stems, like the stems shown in Figure 3-5, so that they can serve a special function:

- **Rhizomes** are stems that grow horizontally just at the soil surface or even underground. The rhizome is the main stem of the plant, which periodically produces a new vertical shoots from its axillary buds. Each shoot may look like a brand new plant from above ground, but they're really all identical clones from the original mother plant. If something breaks the rhizome into pieces, each shoot can continue to grow as a new plant, resulting in asexual reproduction of the original plant. (For more information on asexual reproduction, see Chapter 9.) Examples of plants that grow by rhizomes include ginger, asparagus, bamboo, iris, and many ferns.
- **Stolons** are a lot like rhizomes because they're shoots that grow horizontally along the ground surface, produce new plants, and can lead to asexual reproduction. One difference between stolons and rhizomes is that stolons grow as side shoots off an existing stem, whereas a rhizome is the main stem of the plant. Stolons are often called *runners,* and they're probably most familiar from strawberry plants.

- **Tubers** are the enlarged ends of rhizomes or stolons that are specialized for food storage, usually in the form of starch. A familiar example of a tuber is a potato. Even though people dig potatoes out of the ground, they're not roots — they're actually swollen stems. And the eyes on the potato? Axillary buds!
- **Corms** are the bases of stems that are swollen for food storage. Crocus and gladiolus plants both produce corms. If you buy a bag of crocus or gladiolus "bulbs" to plant in your garden, you're actually buying a bag of corms. (I discuss true bulbs in the upcoming section "Specialized leaves.") Taro, which is used to make poi, is also a corm.
- **Tendrils** are plant structures that are modified to wrap around and cling to things for support. Some tendrils, like the one shown in Figure 3-5, are modified stems, but plants can make tendrils from various plant structures. Cucumber is an example of a plant that clings with tendrils it makes by modifying stems.

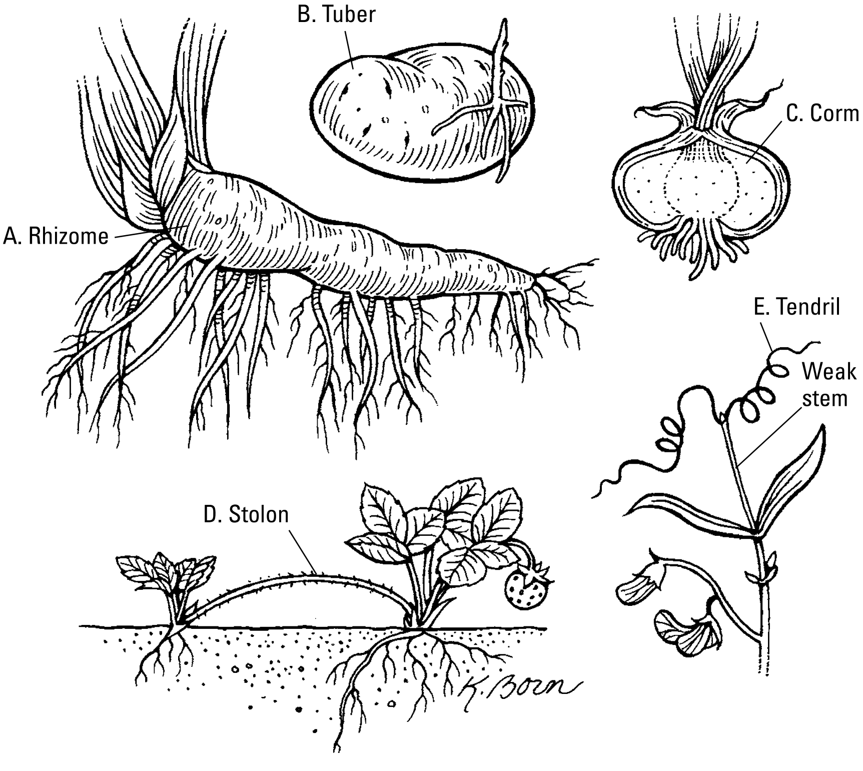


FIGURE 3-5: Types of specialized stems.

Digging Deep with Roots

Roots anchor a plant into the soil, helping it withstand the push of wind and water. Roots grow through the soil, absorbing the water and minerals plants need and transporting them upward into the shoot through vascular tissue. Plant roots also form very important relationships with soil fungi and bacteria that help plants grow.

When a seed germinates, the embryo produces the first root, called the *radicle*. The radicle grows, producing many branch roots and forming the *root system* of the plant. Root systems for a single plant can be huge in relation to the plant itself. Some plant roots extend deep into the soil; others spread out over a great area.

Figure 3-6 shows the two main types of roots systems:

- **Tap root** systems produce thick main roots that have much smaller branch roots. Some tap roots, like those of a carrot, are swollen because they're specialized for food and water storage. Most dicots make tap root systems.
- **Fibrous root** systems produce many fine roots of similar diameter. Grasses, and most other monocots, have fibrous root systems.

In addition to their main root system, some plants produce additional roots called adventitious roots. *Adventitious roots* are roots produced from a plant organ other than a root. For example, the primary roots of monocots die soon after the seed germinates, and then the plants develop adventitious roots directly from the base of the stem.

Regions within roots

Roots grow from their tips, just like shoots, because of an *apical meristem* that produces new cells (see Figure 3-7). The cells of the apical meristem divide frequently, adding new tissue and sending the root telescoping down through the soil. The apical meristem is both valuable and fragile, so plants protect this tissue by covering it with a protective *root cap*. As the apical meristem divides, it pushes cells to both sides, making the root longer and creating the root cap.

A layer of epidermal cells covers the roots, helping protect them and also increasing their ability to absorb water and minerals. Cells of the epidermis can become *root hairs,* single cell projections that extend off the root and increase the surface that's in contact with the soil.

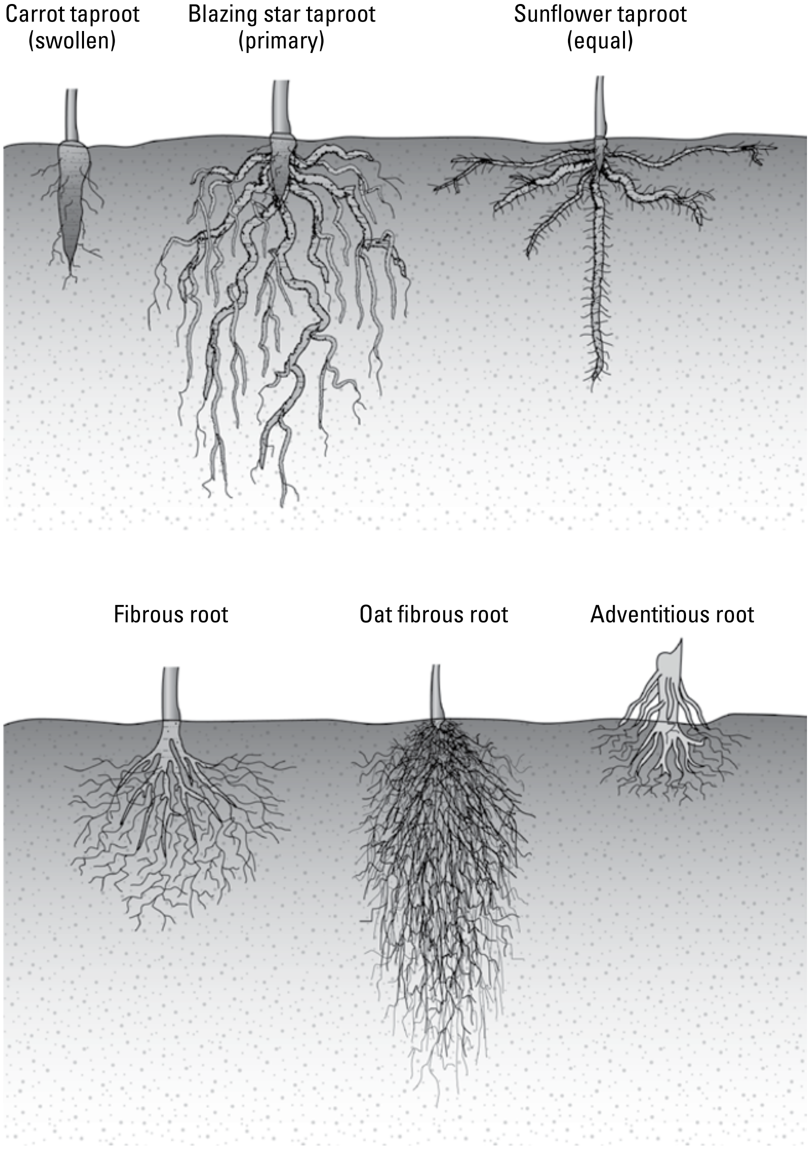

Carrot taproot
(swollen)
Blazing star taproot
(primary)
Sunflower taproot
(equal)
Fibrous root
Oat fibrous root
Adventitious root

FIGURE 3-6: Types of root systems.

REMEMBER

Unlike the epidermis of the stem, the root epidermis has a very thin cuticle so that it can easily absorb water and minerals from the soil. Once water and minerals are absorbed, they're moved into the vascular tissue that forms a *vascular cylinder* in the middle of the root. In most dicots, the primary xylem of the vascular cylinder is arranged in an irregular or cross-shaped pattern. The parenchyma cells of the *cortex* are located in between the epidermis and vascular cylinder. In monocot roots, the vascular bundles form a ring around a central column of pith.

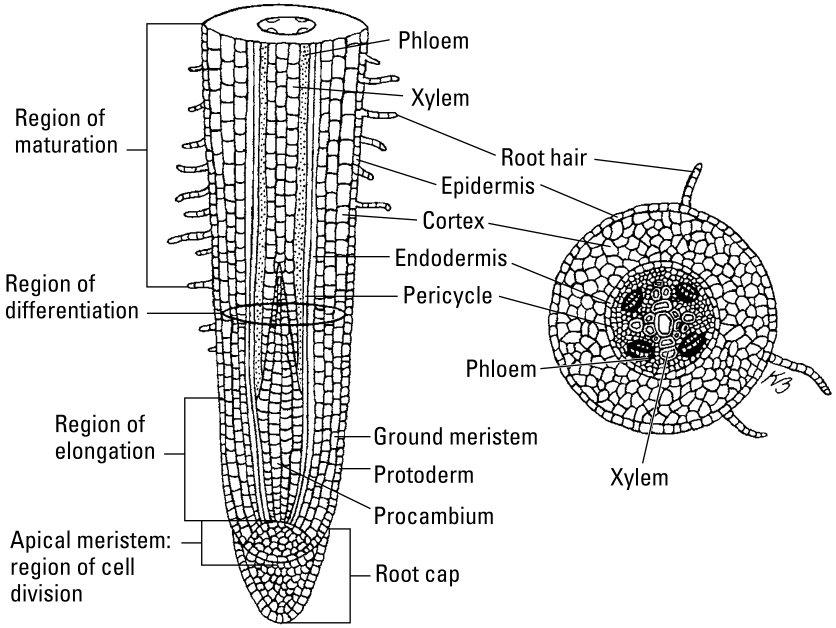

Phloem
Xylem
Region of maturation
Root hair
Epidermis
Cortex
Endodermis
Region of differentiation
Pericycle
Phloem
Region of elongation
Ground meristem
Protoderm
Xylem
Procambium
Apical meristem: region of cell division
Root cap

FIGURE 3-7: The internal anatomy of a dicot root.

Botanists divide roots into four regions, based on the major activities in each:

- **The root cap is located at the very tip of the root, where it provides protection to the apical meristem.** Cells in the root cap produce slippery molecules that help roots slide through the soil and also supports the growth of bacteria that are beneficial to the plant.
- **The region of cell division is located just behind the root cap.** In this zone, the cells of the apical meristem divide to produce new cells. Just like stems, root apical meristems consist of three types of meristematic tissue:
  - **Protoderm** that produces the epidermis.
  - **Ground meristem** that produces parenchyma cells of the cortex.
  - **Procambium** that produces primary xylem and phloem.
- **The region of elongation is located just behind the apical meristem.** In this zone, the root cells expand and get longer. Small vacuoles inside the cells merge to form the large central vacuoles that are common to plant cells.
- **The region of differentiation** (or maturation) is behind the region of elongation. In this zone, root cells change into their final mature forms. Epidermal cells may become root hairs, for example. If the plant is a perennial, secondary growth may begin in this region.

Controlling transport

REMEMBER

Roots have a special layer of cells not found in stems called the *endodermis.* The endodermis is located just at the innermost layer of the cortex and adjacent to the vascular tissue. The endodermis acts kind of like the Great Wall of China — it's a checkpoint for materials entering the plant through the roots.

REMEMBER

Endodermal cells have bands of a waxy molecule, called suberin, wrapped around their walls. These waxy bands, called *Casparian strips,* prevent water and dissolved materials from reaching the vascular tissue by slipping in between cells via the root cell walls. When solutions spreading through the cell walls of the roots reach the Casparian strip, they have to actually enter into a root cell in order to continue to proceed further into the root.

By forcing the solution to enter into the root cell, the plant is able to regulate what types of materials enter. To enter a cell, materials must cross the plasma membrane of the cell. Plasma membranes are very selective and control what is allowed into a cell. (For more on plasma membranes, check out Chapter 2.) Casparian strips also help prevent water loss from the vascular cylinder.

Making lateral roots

The *pericycle* is a layer of cells located at the very outside of the vascular cylinder, just inside the endodermis. The cells of the pericycle, which can consist of one or more layers, remain undifferentiated and capable of cell division even after the cells all around them have matured. The cells of the pericycle divide to produce *lateral roots* that branch off the main root.

TIP

It's easy to confuse lateral roots with root hairs, but they are very different. Lateral roots are multicellular structures with all the tissues of a primary root, originating in the pericycle in the middle of the root. Root hairs are single cell projections of the endodermis.

Lateral roots and root hairs expand the network of plant roots that branch through the soil, forming the *rhizosphere,* the area of soil that surrounds plant roots. Within the rhizosphere, plants form complex relationships with soil microorganisms that influence how plants obtain water and minerals and can even change the chemistry of the soil itself.

TIP

The cells from the outside to the inside of a dicot root are epidermis (root epidermal cells can become root hairs), ground tissue (cortex), endodermis (innermost layer of cortex, contains suberin and casparian strip), pericyle (outer layer of vascular cylinder from which lateral roots originate), phloem (part of vascular cylinder), then xylem (inner part of vascular cylinder).

Secondary growth in roots

In woody dicots and conifers, parts of the pericycle and the parenchyma cells around the primary xylem become a vascular cambium. The cells of the root vascular cambium divide to produce secondary phloem to the outside of the root and secondary xylem to the inside. The patches of new secondary vascular tissue merge together with the primary vascular tissue, forming a circular ring of vascular tissue. Each year, the vascular cambium produces new layers of vascular tissue, causing the secondary xylem to form rings in the roots just like it does in the stems.

The pericycle also gives rise to a cork cambium in the roots. The cork cambium produces cork, which becomes part of the bark of the root.

Specialized roots

In addition to the primary functions of anchoring plants and absorbing water and minerals, some roots specialize for other functions (see Figure 3-8 for examples):

- **Prop roots** are a type of adventitious root that extend from the stem to provide additional support for tall, heavy plants that might have a shallow root system. Corn is a familiar example of a plant that uses prop roots for additional support.
- **Storage roots** store food and water. Beets and carrots, for example, store high amounts of sugar in their roots.
- **Pneumatophores** or breathing roots help plants that grow in very wet areas like swamps get enough oxygen. These roots basically act like snorkel tubes for plants, rising up above the surface of the water so that the plant can get oxygen. Mangrove trees and bald cypress both grow in wet areas and produce pneumatophores.
- **Aerial roots** form when seeds germinate on the branches of other trees, and the growing plant forms roots that wrap around the branch. Aerial roots may grow all the way down until they reach the ground, and sometimes they strangle the host plant. Orchids that grow on other plants produce aerial roots to attach themselves to the plant and to collect moisture and dust from the air. *Buttress roots* are a type of large aerial roots that support tall trees in tropics where the soil is very shallow.

Forming partnerships with soil fungi

Most plants don't work alone to capture water and minerals from the soil. Instead, they form partnerships with fungi called *mycorrhizae*.

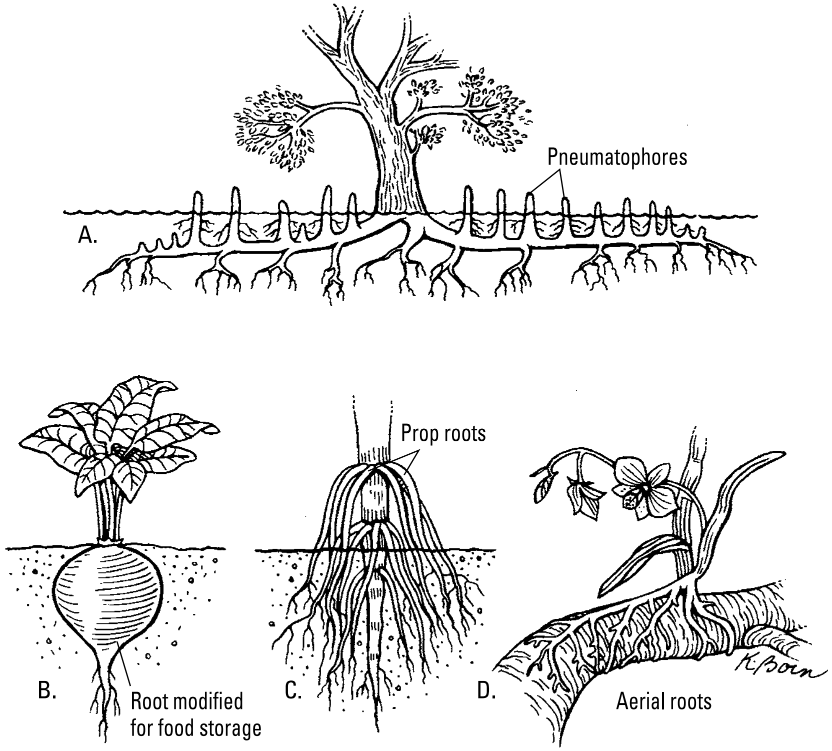


FIGURE 3-8: Types of specialized roots.

The partnership is an example of a *mutualistic symbiosis* that benefits both partners (see Chapter 20 for more on symbiosis and Chapter 17 for more on fungi):

- **The plants give some sugars from photosynthesis to the fungi.** Basically, the plant is offering the fungi a free lunch, which the fungi are quite happy to accept. The fungi grow all over the surface of the plant roots, and some even penetrate into the plant cells.

Reaching Out with Leaves

Leaves are designed to capture as much sunlight as possible while at the same time protecting the plant's water supply. Most leaves have a broad, flat surface that reaches out away from the plant stem in order to intercept the maximum amount of light possible, just like solar panels hanging out there in the sun.

As the sun moves through the sky, plants will even use *solar tracking*, angling their leaves to capture the most sun. When the sun is directly overhead at midday, a bean plant will hold its leaves straight out, turning their flat surfaces directly up toward the sky. Earlier or later in the day, when the sun is at an angle, the plant will let the leaves drop down so that the flat surface is pointed at the right angle to still face the sun.

Leaf structure

Leaves begin as tiny *leaf primordia*, little embryo leaves within the buds of plants. Most leaves have two parts:

- The **blade,** which is the flattened part of the leaf. A network of veins containing vascular tissue runs through the leaf blade.
- The **petiole,** or stalk, of the leaf. Some plants have a pair of appendages, called *stipules*, at the base of the petiole.

TIP

Some of the food you eat is made of leaves. When you have a salad, you eat the blades of the lettuce leaves. If you have onions in your salad, you're eating swollen leaves. And if you eat celery, you're eating giant petioles!

Leaves have the same tissues as do stems and roots. Figure 3-9 shows the organization of these tissues inside a leaf:

- **The epidermis is the outer protective layer of cells that cover the leaf.** Leaves need to exchange gas with the environment — for example, they need to take in carbon dioxide for photosynthesis — but they also need to minimize water loss. Two features of leaves help them exchange gases without losing too much water:
  - **A waxy *cuticle* coats the outer surface of the epidermis.** The cuticle helps prevent water loss from the leaf to the air.
  - ***Guard cells* within the epidermis control whether the pores in the leaf, called *stomata* (also called *stomates*), are open or closed.** So, by controlling the guard cells, plants make sure that they open their stomata only when it's safe, and they won't lose too much water. When the guard cells fill up with water, they swell and pull away from each other, opening the stomata. When the guard cells lose water, they become flaccid and move toward each other, closing the stomata.
- **Parenchyma cells make up most of the interior of the leaf.** These cells form the main photosynthetic region of the plant, called *mesophyll,* which forms the majority of the tissue between the upper and lower surfaces of the leaf. Mesophyll may contain two different types of parenchyma cells:

- The upper part of the mesophyll consists of tall, columnar cells called *palisade parenchyma*. These cells are packed together directly under the upper epidermis to absorb as much light as possible in their many chloroplasts.
- The lower part of the mesophyll contains loosely arranged parenchyma cells, called *spongy parenchyma,* that have lots of air spaces between them.

- **Vascular tissue makes up the veins of the leaf.** The vascular tissue brings sugar from the leaves into the stem of the plant and also conducts water from the plant out into the leaves. Each vein contains xylem and phloem tissue surrounded by a layer of protective, thick-walled fiber cells called the *bundle sheath*. The pattern of veins is typically different in monocots and dicots:
  - Monocot leaves usually have *parallel veins,* where the veins line up in parallel lines.
  - Dicot leaves usually have *reticulate,* or *netted, veins,* where the veins form a branching network in the leaf.

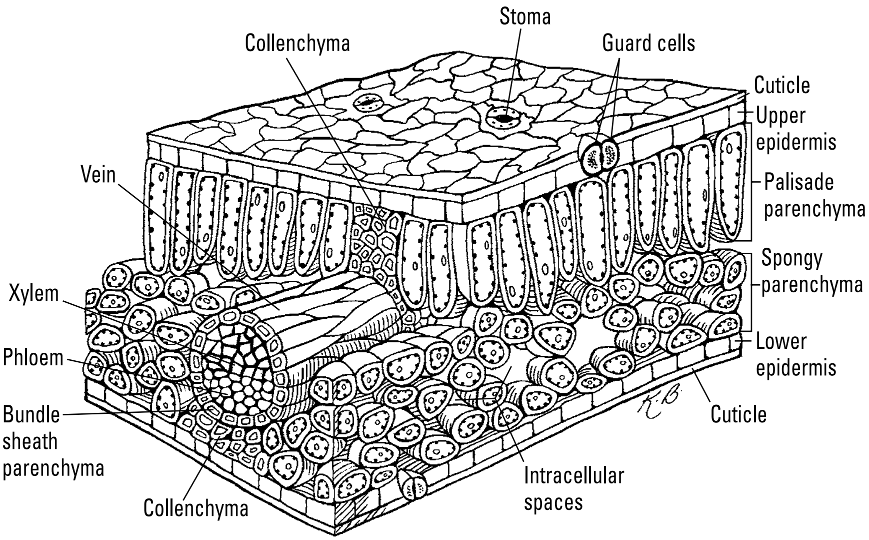

Stoma
Collenchyma
Guard cells
Cuticle
Upper epidermis
Vein
Palisade parenchyma
Spongy parenchyma
Xylem
Phloem
Lower epidermis
Bundle sheath parenchyma
Cuticle
Intracellular spaces
Collenchyma
K.B.

FIGURE 3-9: Internal anatomy of a leaf.

Leaf types

If you are interested in identifying plants when you are outside in nature or if you want to forage for wild plants, you might find it useful to learn some of the terminology that botanists use to describe leaves. I'm going to introduce some of the more common terms in this section, but if you are very interested in plant identification you might want to pick up a reference book to plant identification terminology.

Leaves come in many different shapes, like those shown in Figure 3-10:

- Linear leaves are long, thin, and symmetrical like the leaves of a rosemary plant. Lanceolate leaves are also narrow, but they're a little broader toward the base.
- Elliptic leaves are oval, with the widest part in the middle, like the leaves of a cherry tree. Ovate leaves are similar, but are a little wider at the base, like an egg.

You can also describe leaves by the pattern along the edge, or *margin*, of the leaf, like those shown in Figure 3-10.

- Entire margins are smooth, like the edge of a corn leaf.
- Dentate margins have a toothed appearance, with the notches pointing outward away from the leaf like those on a strawberry leaf. Serrated margins are also toothed, but the teeth point towards the tip of the leaf like those on a birch leaf.
- Lobed margins form deep and gentle curves, like those of oak leaves.

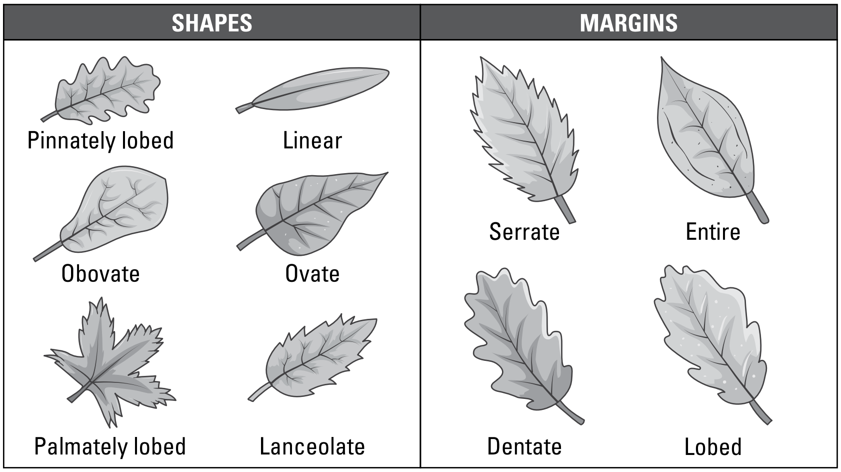


FIGURE 3-10: Some examples of leaf shapes and leaf margins.

TIP

To tell whether a leaf is simple or compound, look for the axillary bud. A simple leaf has a bud in the axil between the leaf and the stem. In a compound leaf, the leaflets might look like individual simple leaves, but they won't have any buds in their axil. The only bud will be found at the base of the entire compound leaf.

REMEMBER

- *Simple leaves* have a single blade.
- *Compound leaves* have a blade that is separated into smaller *leaflets.*

Several different kinds of compound leaves exist:

- *Pinnately compound* leaves have many small leaflets that attach along an axis called a *rachis*.
- *Palmately compound* leaves have several leaflets that attach at the same point so that the leaflets look like fingers on a hand.
- *Doubly compound* leaves have leaflets that are divided again into more leaflets.

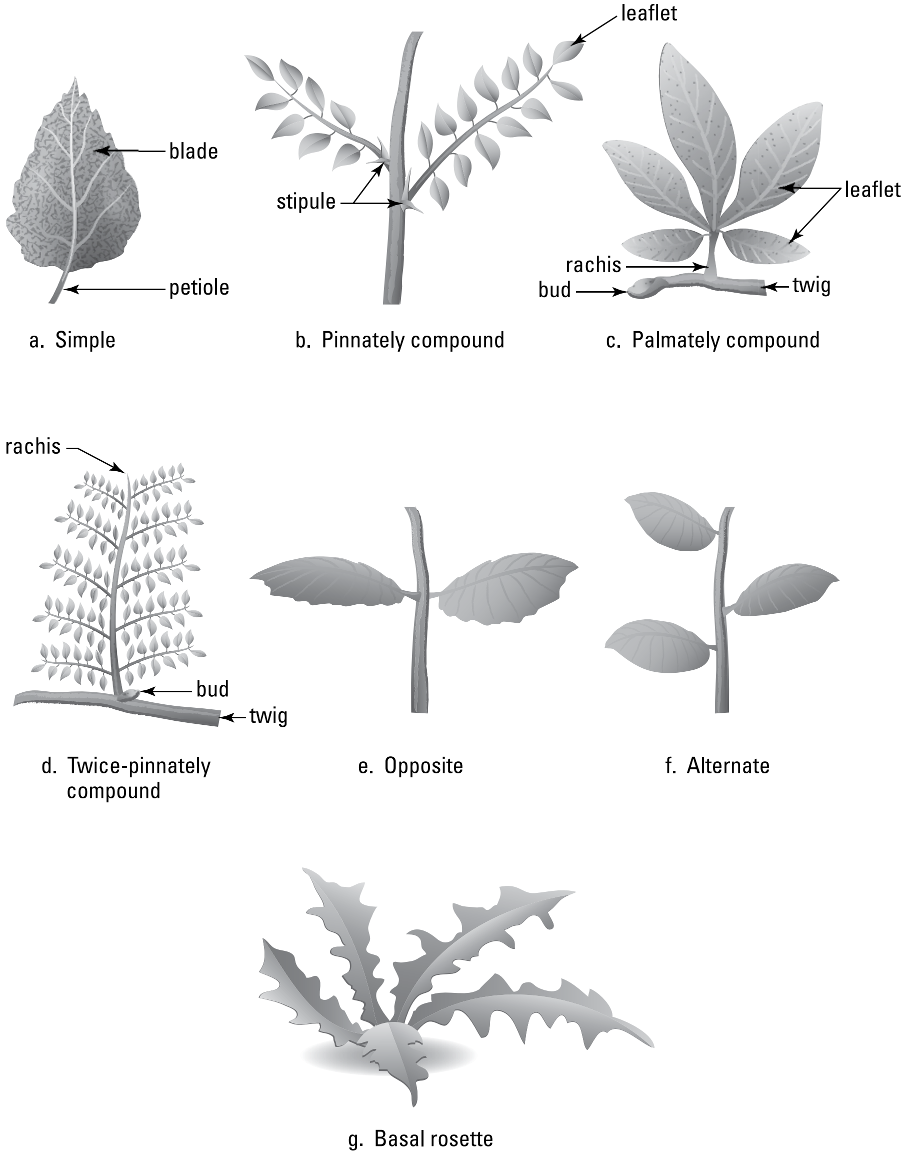
Leaf arrangements

Leaves can attach to stems in different ways, forming numerous leaf arrangements. Figure 3-11 shows the three most common *leaf arrangements*:

- *Alternate leaves* occur when leaves are attached in a spiral arrangement along the stem, with one leaf at each node.
- *Opposite leaves* occur when two leaves attach to the stem directly opposite each other so that two leaves appear at each node.
- *Whorled leaves* occur when several leaves attach to a stem at a single point so that three or more leaves appear at a single node. When the whorled leaves attach at the base of the plant, botanists call the leaves a *basal rosette.*

A CABBAGE BY ANY OTHER NAME

Do you like broccoli? How about Brussels sprouts, kale, cabbage, or cauliflower? If you like one, you might like them all — they're all varieties of the same plant. People created each of these vegetables by breeding wild cabbage, *Brassica oleracea,* and selecting for different traits. Just like a farmer might breed his favorite milk cow or a dog fancier selects dogs with a certain trait, farmers chose cabbages that had a unique feature and then bred them to each other over and over until they developed a variety that looked pretty different from the original wild parent because one feature was greatly exaggerated. When you eat broccoli or cauliflower, you're eating the flowering part of the plant, plus maybe a little stem if eat part of the stalk. When you eat kale or cabbage, you're eating the basal rosette of leaves. And when you eat Brussels sprouts, you're eating giant axillary buds!


leaflet
blade
stipule
leaflet
rachis
bud
twig
petiole
rachis
bud
twig

a. Simple

b. Pinnately compound

c. Palmately compound

d. Twice-pinnately compound

e. Opposite

f. Alternate

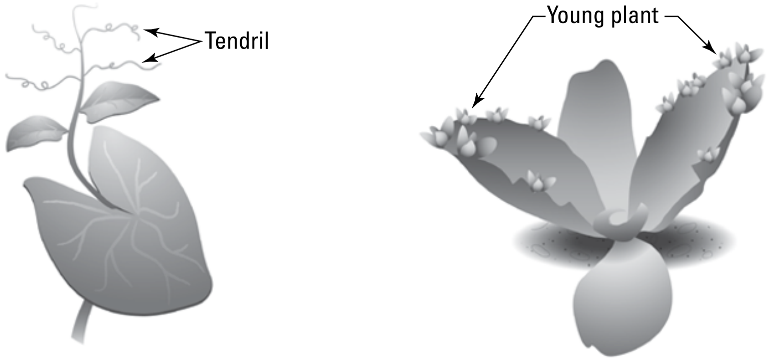
g. Basal rosette

FIGURE 3-11: Types of leaves and leaf arrangements.

Specialized leaves

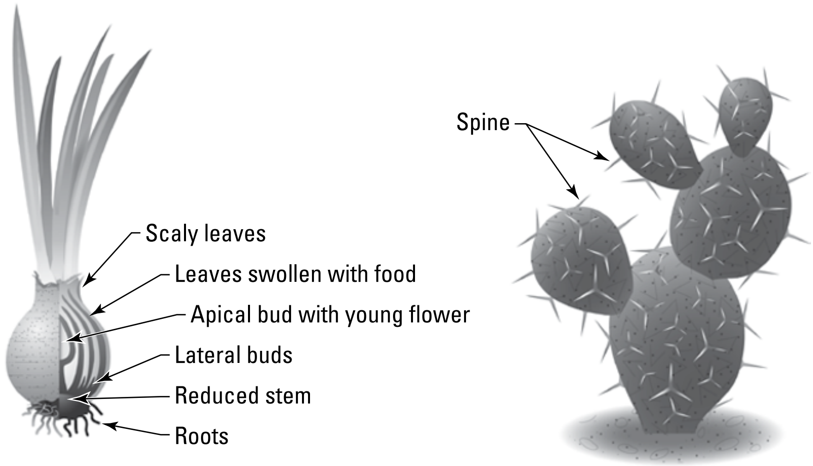
Some plants modify some leaves either so that they can perform additional functions or to protect the plant from water loss. Figure 3-12 shows some structures that plants form by modifying their leaves:

- *Tendrils* wrap around adjacent stems or other structures. Pea plants are a familiar example of a plant that climbs using tendrils that originate from modified leaves.
- *Reproductive leaves* allow plants to reproduce asexually by producing tiny plantlets along their edges. The plantlets fall off the leaves and grow into new individuals.
- *Bulbs* are clusters of leaves that have fleshy food-storing bases. Onions are an example of edible bulbs.
- *Spines* protect plants from grazers and reduce water loss. The sharp spines on a cactus are the only leaves they produce.
- *Bracts* are leaves that are modified either to protect something or sometimes to attract a pollinator. The showy, red bracts on a *Poinsettia* plant look like petals, but the plant clusters the real flowers in the center of the red bracts.
- *Succulent plants* have thick, fleshy leaves that are modified for water storage. *Aloe vera* is a good example of a succulent plant that's filled with a moist, sticky sap.
- *Cones* and *flower parts (sepals, petals, stamens, and carpels)* also evolved from leaves that were modified for reproductive functions. Petals and cone scales still have a flat leaf-like appearance that suggests their origins.


Tendril
Young plant

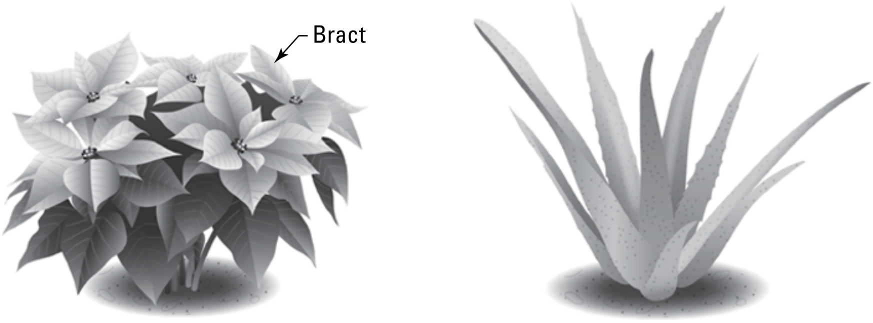
a. Tendrils

b. Reproductive leaves


Scaly leaves
Leaves swollen with food
Apical bud with young flower
Lateral buds
Reduced stem
Roots
Spine

c. Bulb

d. Spines



e. Bracts

f. Succulent leaves

FIGURE 3-12: Some structures that plants form by modifying their leaves.

IN THIS CHAPTER

- Distinguishing between types of spores
- Discovering the advantages of seeds
- Checking out cones
- Exploring the structure of flowers
- Finding out about fruit

Chapter 4

Reproductive Structures: Spores, Seeds, Cones, Flowers, and Fruits

Many plants and other organisms, such as molds, reproduce by simple structures called spores. Two groups of plants, the cone-bearing plants and the flowering plants, evolved an even better reproductive structure — the seed. Flowering plants use flowers to ensure their reproductive success and then package their seeds in fruits that help disperse new plants away from the parent. This chapter presents the structure and function of these plant reproductive structures.

Reproducing with Spores

If you study biology long enough, you'll hear the word *spore* many times. A *spore* is a reproductive cell that is capable of growing into a new organism or structure without uniting with another cell. Spores made by organisms that live on land usually have protective outer layers and can survive for some time without water. Because biologists define the word *spore* so broadly, lots of different kinds of living things make structures that biologists call *spores*. You've probably seen black or green mold spores in your kitchen on some old bread, cheese, vegetables, or fruit. Molds, and other types of fungi reproduce by spores, as do many different kinds of eukaryotic microorganisms (for more on fungi, flip to Chapter 17). And, as you may have guessed because I'm including them in this chapter, plants make spores as part of their life cycles, too.

Plants make spores during sexual reproduction. Plant life cycles are complicated because every plant has two different forms, one called a *sporophyte* and one called a *gametophyte* (sometimes you only see one form because the other one is microscopic). Spores enter into the picture when the sporophytes produce spores by a type of cell division called *meiosis*. Spores then grow into the gametophytes, which are the forms that make sperm and egg. (For more details on meiosis and the life cycles of plants, check out Chapter 9.)

Protecting the Offspring with Seeds

Spores are nice, but seeds are better. (See Table 4-1 for a comparison.) Seeds not only have protective coverings, they also have food reserves, helping plant embryos to survive away from the parent plant. Seeds can remain dormant for hundreds, or even thousands of years, before they begin to grow!

TABLE 4-1 Plant Spores versus Seeds

	Spores	Seeds
Cells	Single cells	Multicellular containing an embryo, nutritive tissue, and a seed coat.
How and where are they produced?	Produced by sporophytes in structures called sporangia by a type of cell division called meiosis.	Seeds develop from ovules, female parts of plants that contain the egg and are fertilized by sperm.
What will it grow into?	A gametophyte	A sporophyte

Seeds *germinate*, or begin to grow, when conditions are right for the new plant. The amount of time seeds remain dormant depends upon a combination of internal signals, such as hormones (see Chapter 8), and external signals from the environment, such as the temperature and the availability of light and water. Some seeds germinate within weeks of being released from the parent plant, whereas others remain dormant for months to years. Over time, seeds will begin to die if they don't encounter the right conditions for growth.

Two groups of plants evolved the ability to make seeds:

- ***Gymnosperms* are plants that make seeds, but don't make flowers and fruits**. Gymnosperms often package their seeds in cones. Gymnosperms include pine trees, Ginkgo trees, and cycads. (To explore this plant group, see Chapter 15.)
- ***Angiosperms* are plants that make seeds, flowers, and fruits.** In other words, angiosperms are the familiar flowering plants (see Chapter 16). Two groups of plants — *monocots* and *dicots* — within the angiosperms have distinct structural differences, both in their vegetative and reproductive structures. (For more on these groups, see Chapter 3.) Botanists define these two groups of angiosperms based on the number of seed leaves, or *cotyledons*, that are attached to the plant embryo within the seed:
  - *Monocots* have one cotyledon.
  - *Dicots* have two cotyledons.

Seed structure

REMEMBER

Seeds contain new plant embryos along with stored food and are covered by a *seed coat* that protects the seed from destruction. The seeds of each plant group differ in the number of cotyledons and the source of the food for the embryo:

- **Gymnosperms, such as pine, produce embryos with multiple cotyledons that use primary endosperm as food.** *Primary endosperm* develops from maternal tissue that wasn't fertilized so that it contains two sets of chromosomes (is diploid).
- **Dicots produce embryos with two cotyledons.** Some dicots use the cotyledons as food, whereas most others use a tissue called *endosperm*. The cotyledons are part of the embryo, so they have two sets of chromosomes (are *diploid*). Endosperm develops from a cell that is fertilized by two sperm, so it contains three sets of chromosomes (is *triploid*). (See Figure 4-1 for a drawing of a dicot seed.)
- **Monocots produce embryos with one cotyledon that use endosperm as food.** Like the endosperm of dicots, the endosperm of monocots is triploid. (See Figure 4-2 for a drawing of a monocot seed.)

Dicot seeds

If you look closely at a dicot seed, such as a bean or a peanut, you can study its parts (see Figure 4-1):

- The outermost covering is the *seed coat*. If you examine the seed coat carefully, you'll see a couple of tiny marks: the *hilum,* a small scar that marks where the seed was attached to the ovary wall inside the parent plant, and the *micropyle,* a tiny hole that allowed the pollen tube to enter during fertilization.
- If you're looking at a roasted peanut or if you soak a bean seed for a while, you can take the outer covering off and examine the inside part of the seed. The seed will split apart into two halves, which are mostly the two large cotyledons.
- The *embryo* is tucked in between the two cotyledons. If you look closely, you can see a tiny shoot called a *plumule* and the little stub that will develop into the stem and roots, called the *hypocotyl-radicle axis*.

Dicot seeds from peas and beans are a little bit different from other dicots because they belong to the group of dicots that uses the cotyledons as food for the embryo. As a result, the cotyledons in these seeds are very large. Most other dicots use endosperm as food for the embryo. In these seeds, the cotyledons are much smaller and look like tiny leaves at the top of the embryo. The bulk of the tissue surrounding the embryo is endosperm.

As dicot seeds germinate, the food stored in the cotyledons or endosperm provide the growing embryo with energy and building material for growth. Figure 4-1B shows the germination of a bean seed as an example of early dicot development:

1. **The radicle begins to grow and emerges from the seed to form the first root, called the *primary root.***
2. **The hypocotyl elongates, pushing its way out of the seed and above the soil.**

   The cotyledons protect the upper part of the embryo, called the *epicotyl,* as it emerges from the soil.
3. **Below the soil, secondary roots begin to branch off of the primary root.**
4. **When the hypocotyl emerges into the light, it straightens out and the epicotyl becomes visible, revealing a pair of true leaves and the apical meristem of the plant.**

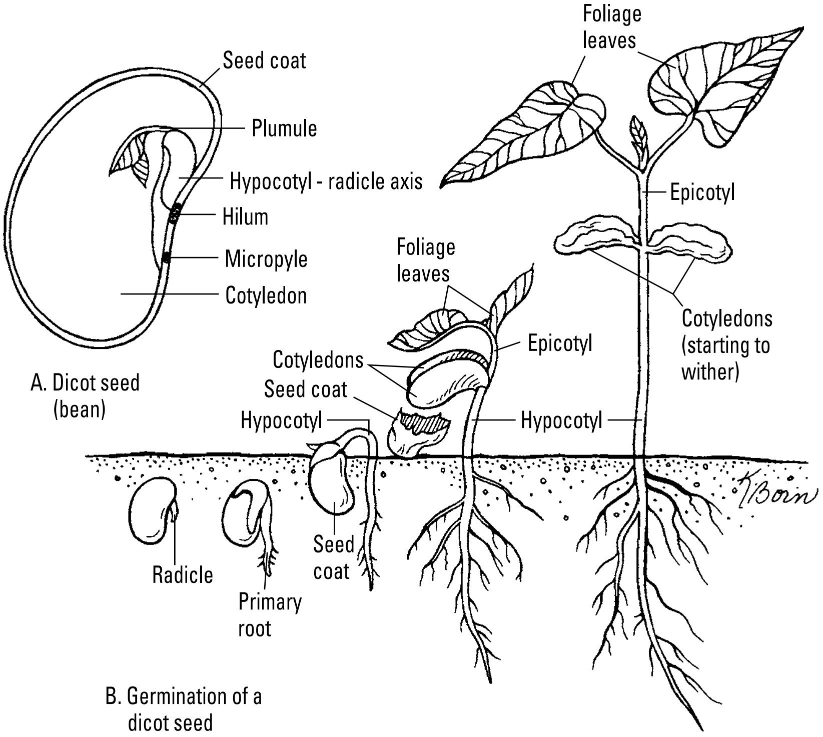

Seed coat
Plumule
Hypocotyl - radicle axis
Hilum
Micropyle
Cotyledon
A. Dicot seed (bean)
Foliage leaves
Epicotyl
Foliage leaves
Epicotyl
Cotyledons (starting to wither)
Cotyledons
Seed coat
Hypocotyl
Hypocotyl
Hypocotyl
Radicle
Primary root
Seed coat
K Born
B. Germination of a dicot seed

FIGURE 4-1: Structure and germination of a dicot seed.

5. **The leaves expand and begin to do photosynthesis.**

   In many dicots, including some beans, the cotyledons turn green and also do photosynthesis until they wither and drop off the plant. (If you're a gardener, you may have noticed that the first leaves of a plant look different from later leaves. That may be because the first leaves were actually the cotyledons rather than the "true" leaves of the plant.)

Monocot seeds

To study the parts of a monocot seed, you can take a close look at a corn kernel (shown in Figure 4-2):

- The outermost layer of a corn kernel is the *pericarp*. If you remove the pericarp, the next layer you'll find is the *endosperm* that supplies the embryo with food.
- Like dicots, monocot embryos have a plumule and a radicle. In monocots, however, the plumule is enclosed in a tubular structure called the *coleoptile,* and the radicle is enclosed in the *coleorrhiza.* Monocot embryos have only one thin, leaf-like cotyledon.

WARNING

A corn kernel is actually a type of dry fruit called a *caryopsis*, or *grain*, that contains a single seed. However, the wall of the fruit, called the *pericarp*, is fused to the seed coat, so everything inside the kernel is part of the seed.

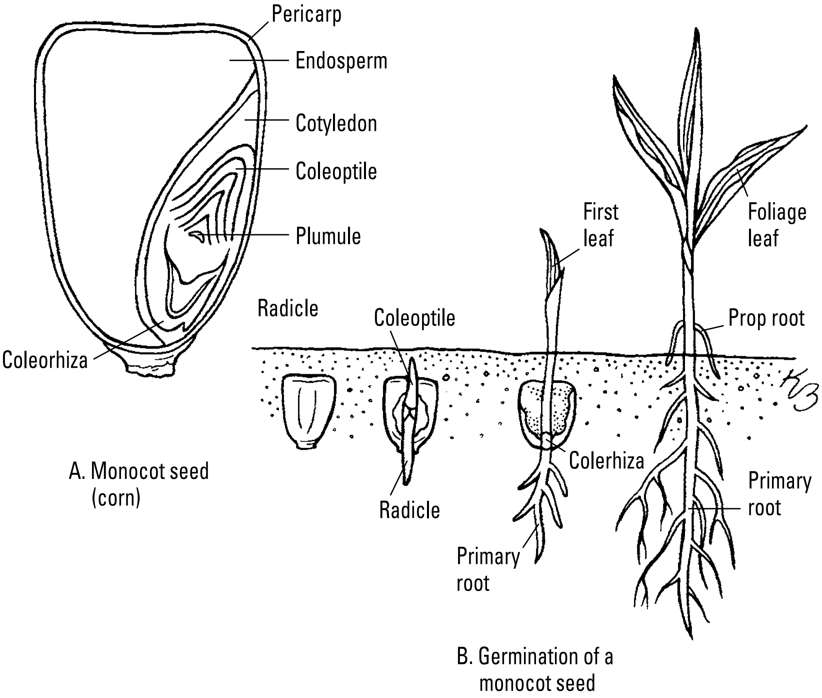

Pericarp
Endosperm
Cotyledon
Coleoptile
Plumule
Radicle
Coleorhiza
A. Monocot seed (corn)
Coleoptile
Radicle
First leaf
Foliage leaf
Prop root
Colerhiza
Primary root
Primary root
B. Germination of a monocot seed

FIGURE 4-2: Structure and germination of a monocot seed.

The endosperm provides the growing monocot embryo with energy and building material for growth. Figure 4-2B shows the germination of a corn kernel as an example of early monocot development:

1. **The radicle grows first, piercing the kernel and growing downward into the soil to form the primary root.**
2. **The primary leaf of the shoot grows upward, pushing its way out of the kernel and the soil.**

   As the leaf grows, it's protected by the tube-like coleoptile.
3. **Once the primary leaf reaches the light, it pushes through the coleoptile and begins to expand.**
4. **Under the soil, lateral roots begin to develop from the primary root.**
5. **In monocots, the primary root aborts in the seedling and adventitious roots called prop roots develop from the stem and push their way into the soil.**

Organizing Reproduction in Cones

Reproductive structures like cones and flowers evolved from specialized leaves called *sporophylls*. Sporophylls are leaves that produce spore-producing structures called sporangia on their surface. As plants evolved to protect the sporangia and produce spores more efficiently, the leaves with sporangia became more specialized, losing their photosynthetic function and becoming shorter and thicker and more densely packed on the stem. Over time, these tight bunches of sporophylls evolved into the cones and flowers you see today.

REMEMBER

The sporophylls of some gymnosperms are spirally arranged into structures called *strobili* or *cones.*

Gymnosperms (see Chapter 15) produce spores that grow into gametophytes right inside the cone. Some cones, such as those of cycads, are bisexual, producing both male and female gametophytes. Other cones, such as those of conifers, are either male or female and produce gametophytes of only one sex. After sexual reproduction occurs, seeds develop inside the cones. Next time you find a cone on the ground, try breaking it open. If it is a relatively fresh cone, you might find seeds inside. (Pine nuts are the seeds from certain species of pine.) If it is an older cone, the seeds may be gone, but you might be able to see the depression left behind by the seeds.

Finding a Mate with Flowers

Plants have sex! You may not have thought about it, but whenever you've enjoyed the beauty of a flower, you've basically been admiring an advertising campaign designed to find a plant a suitable mate. Some plants, like the seedless vascular plants (see Chapter 14) and gymnosperms (see Chapter 15) are more discreet about their sexual reproduction, but the flowering plants really like to dress up and show off.

Flower structure

All flowers have four basic parts derived from modified leaves and a supporting stalk. At the base of the flower, you'll find the stalk of the flower, called the *peduncle*. As the penduncle produces a flower bud or cluster of buds, it swells to form the base of the flower, which is called the *receptacle.* Other parts of the flower — like the petals — grow in *whorls,* or rings, around the receptacle.

You can see the four basic types of parts of flowers in Figure 4-3:

- **The first, outermost whorl of parts that grows from the receptacle is the *sepals.*** Sepals are petal-like structures that are often green. All together, the whorl of sepals is called the *calyx.* When the flower bud is closed, the calyx helps protect the rest of the flower. Sometimes, sepals have bright colors and look like petals. When the sepals and petals look the same, some botanists call all of them *tepals* instead of sepals or petals.
- **The next whorl of parts is the one you're probably most familiar with — the *petals.*** All the petals together are called the *corolla*. The reason you see so many different looking types of flowers are because of the ways plants modify their corollas to attract different pollinators. (See the section "Moving pollen," later in this chapter.)

  Together, the sepals and petals form the *perianth* of the flower.

REMEMBER

- **After the petals, flowers have a whorl of male parts called *stamens.*** Flowers can have a few or many stamens. Each stamen has two parts:
  - The little bags of pollen at the tips of the stamens are called *anthers*. Anthers contain sporangia. The spores produced there develop into pollen grains containing sperm cells.
  - The slender stalks that support the anthers are called *filaments*.
- **The most central whorl of parts within a flower consists of female *carpels* — green, vase-like structures.** In many flowers, more than one carpel fuses together to form a compound carpel, also called a *compound pistil*.

  Each carpel has three parts:
  - The tip of the carpel is the *stigma.* Pollination occurs when pollen grains land on the stigma.
  - The long, tubular part of the carpel is called the *style*. Pollen grains grow long tubes down through the style in order to reach the base of the carpel.
  - The swollen base of the carpel is the *ovary.* Inside the ovary are chambers that contain one or more *ovules.* After the ovules are fertilized with sperm from the pollen, they will develop into seeds. (For more details on fertilization and seed development in flowering plants, check out Chapter 16.) Ovaries with one chamber are *simple ovaries;* ovaries with multiple chambers are *compound ovaries.* Each chamber forms from a single carpel, so compound ovaries occur when carpels fuse together.

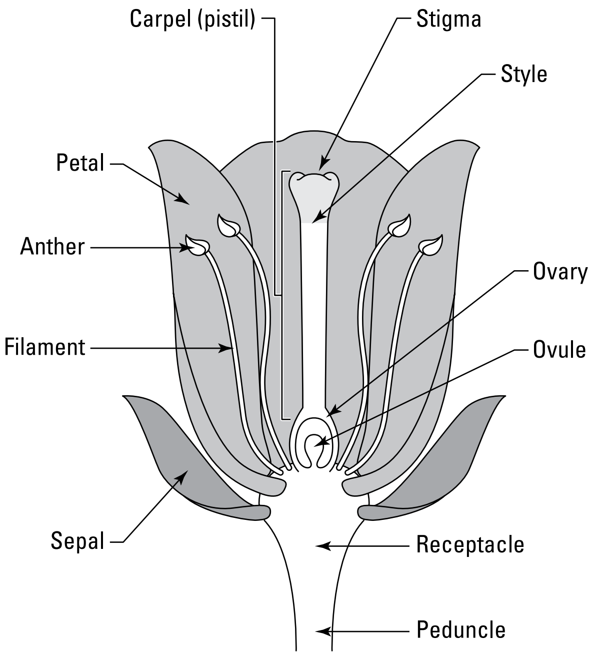


FIGURE 4-3: Parts of a typical flower.

REMEMBER

One way that flowers can look different from each other is based on the position of the ovary relative to the calyx and corolla, as shown in Figure 4-4, and this trait can be useful when you are trying to identify a flowering plant. If the calyx and corolla are attached to the receptacle underneath the ovary, botanists say the ovary is *superior* (Figure 4-4A). Likewise, if the calyx and corolla are attached to the receptacle above the ovary, botanists say the ovary is *inferior*. (See Figure 4-4C.) An ovary that is only halfway below the attachment point is a half-inferior ovary (see Figure 4-4B).

The two groups of flowering plants, dicots and monocots, make flowers with different numbers of petals and other flower parts. Dicot flowers typically have parts in fours and fives, or multiples of fours and fives, while monocot flowers typically have parts in threes or multiples of threes.

TECHNICAL STUFF

Botanists call the entire whorl of male parts the *androecium* and the whorl of female parts the *gynoecium.*

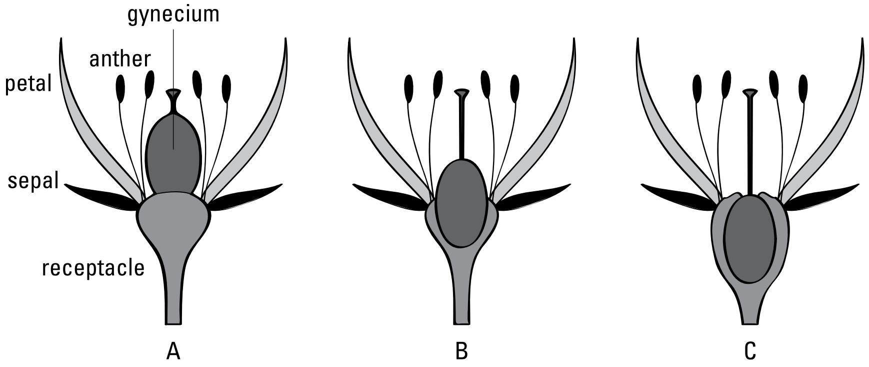


FIGURE 4-4: Ovary insertion within a flower.

Moving pollen

The world is full of beautiful and amazing flowers in many shapes and colors. The reason that flowers are so diverse is because each type of flower has a different strategy for spreading and gathering pollen. Some flowers are tailored to a particular animal pollinator, while others use wind to move their pollen around. You can guess the strategy that a flower uses by the way it looks and smells:

- Plants that attract bees to help with pollination often make blue or violet flowers, because those are the colors that bees see best. Some petals even have markings that are invisible to humans but visible to bees. (If you search the Internet for pictures of flowers under ultraviolet light, you can see some of these markings.)
- Plants that attract moths are often white and strongly scented so that moths can find the flowers in the dark.
- Hummingbirds see red well, so plants that are advertising for hummingbirds often make red flowers and provide sweet nectar as a reward. The petals on some bird-pollinated flowers join together to form a tube-like corolla. The beaks of birds have no problem reaching down into these tubes to get nectar and pollen. (Next time you see a hummingbird feeder in a store or your own backyard yard, notice how the human design of these feeders mimics nature — they are typically red and have tubular openings for the birds to access the sugar solution.)
- Some flowers attract beetles or flies as pollinators. Some of these flowers produce obvious advertising with their reddish, rotten meat appearance or smells. Others are more subtle, such as those that look like clusters of small white flowers. This can be a little startling when you lean in to smell the flowers and get a whiff of a urine-like smell!

- In plants that don't attract animals, such as those that use wind for pollination, the flowers may not have a corolla at all. In grasses, the female parts of the flower have feathery extensions designed to capture pollen as it blows by in the wind.

Flower arrangement

Some plants produce solitary flowers, but others cluster flowers together along a single stem. An *inflorescence* is a cluster of flowers along a single stem or series of stems. The little stems that extend to each flower in an inflorescence are the *pedicels*, and the central stem of an inflorescence is the *rachis. Rachis* is the same term that botanists use for the central stem of a compound leaf (refer to Chapter 3).

Leaves may grow from the base of the entire inflorescence, or at the base of each flower, or both. Sometimes, the leaves around the inflorescence look different from the rest of the leaves on the plant. Botanists call these modified leaves *bracts*.

Recognizing the type of inflorescence of a flowering plant is another helpful clue to its identity. Figure 4-5 shows several different types of inflorescences:

- ***Racemes* form when a plant produces flowers on short pedicels branching from a main stem or rachis.** The flowers at the base of the main stem bloom first so that the stem is arranged with the oldest flowers at the base and the youngest flowers toward the tip. Wildflowers like foxglove, lupine, and bluebonnets produce their flowers on racemes.
  - ***Panicles* are compound racemes — each axillary stem along the main stem branches into a tiny raceme.** The big, feathery inflorescences of some grasses are panicles, as are familiar garden flowers like lilac and astilbe.
  - ***Spikes* are a type of raceme where the flowers are *sessile*, meaning they sit close to the rachis rather than extending off on pedicels.** Lavender and other mints are examples of plants that produce their flowers on spikes.
- ***Catkins* are spikes of drooping cylinders of tightly packed flowers that may lack petals.** Some familiar trees that make catkins are birch, willow, and oak.
- *Umbels* form when a plant makes many short flowering stems that extend from the same point on the main stem, similar to the way the spokes of an umbrella extend out from one point on the shaft. Like racemes and panicles, umbels can be simple or compound: In a compound umbel, each of the short stems that extend from the main stem branch into miniature umbels called *umbellates.* Queen Anne's lace, or wild carrot, is a familiar wildflower that produces flowers in compound umbels, such as the one in Figure 4-5.

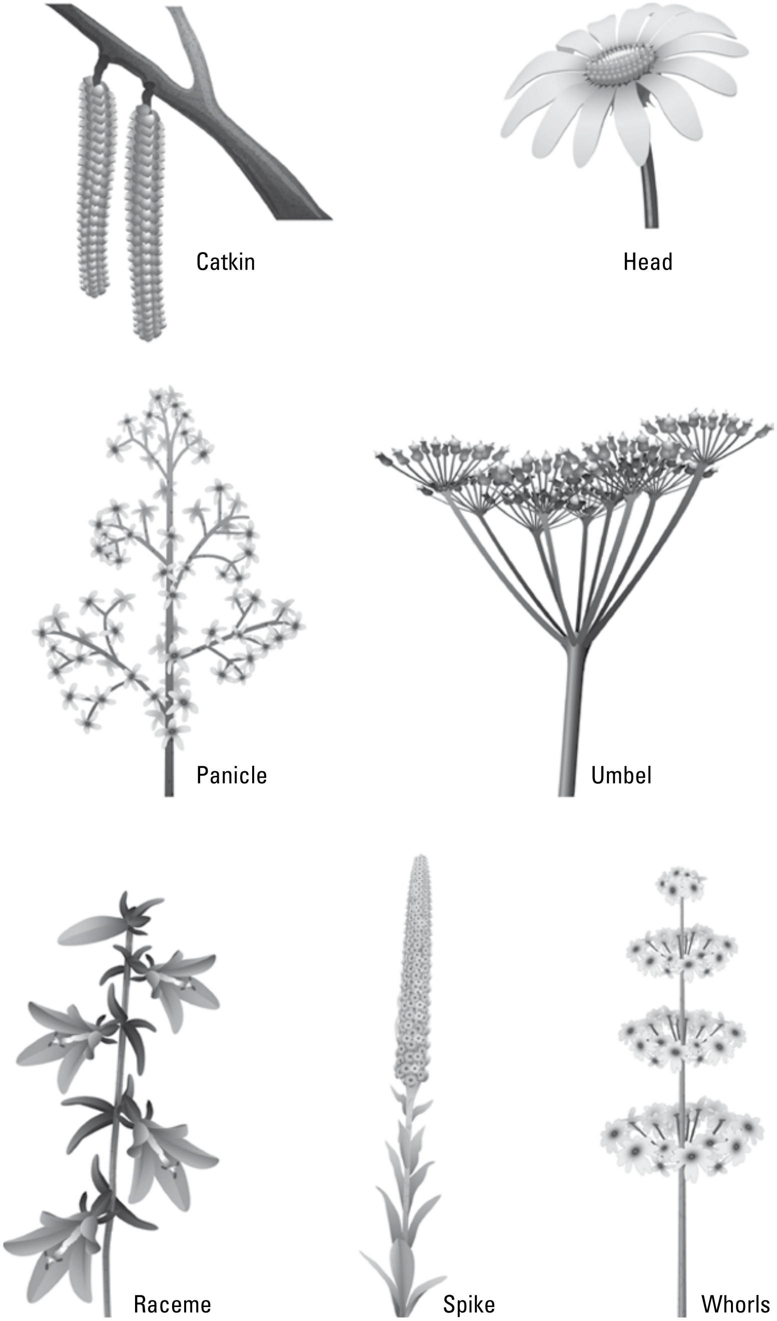

Catkin
Head
Panicle
Umbel
Raceme
Spike
Whorls

FIGURE 4-5: Types of inflorescences.

- **A *head,* or *capitulum,* looks like a single flower but is actually a group of many flowers all on a common receptacle.** Some very familiar flowers, such as daisies, asters, and sunflowers, may have been fooling you all these years into thinking you were looking at a single flower, but the part of the flower that looks like petals is actually many tiny *ray flowers,* and the middle of the flower is many tiny *disk flowers.* The disk and ray flowers are arranged on a single receptacle.

Packaging the Seeds in Fruits

REMEMBER

All plants that make flowers also make fruit. Once a flower has been pollinated and the sperm fertilize the eggs in the ovules, the ovary of the flower develops into a fruit. The ovary wall becomes the flesh or outer covering of the fruit, and the ovules develop into seeds.

As the ovary ripens into a fruit, it develops into three separate regions (see Figure 4-6):

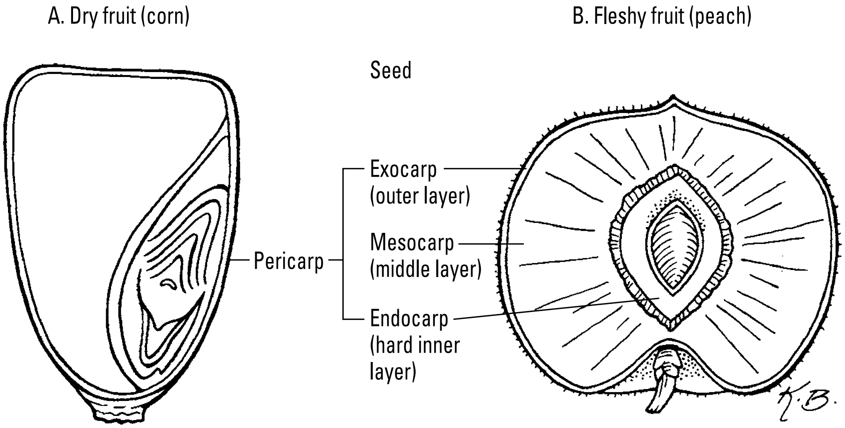


FIGURE 4-6: Regions of a fruit.

- The skin of the ovary becomes the *exocarp,* or outside of the fruit.
- The innermost layer of the ovary that's closest to the ovules develops into the *endocarp,* or inner boundary around the seeds.
- The *mesocarp* is everything in between the exocarp and the endocarp.

REMEMBER

Together, the three layers of a fruit form the *pericarp*.

Fruit types

Fruits come in many different forms from soft and fleshy to hard and dry. And just as some plants produce single flowers and others produce inflorescences, some fruits are made from single ovaries, while others are made from multiple ovaries joined together. Figure 4-7 shows some examples of the many types of fruits produced by flowering plants.

WARNING

The way most people use the word fruit and the way that botanists use the word fruit can be quite different. In nonscientific terms, people tend to think of fruits as sweet. But to a botanist, any ripened ovary is a fruit. So, while it's true that apples, oranges, and grapes are fruits, so are tomatoes, nuts, cucumbers, string beans, maple "helicopters," grains of grass, and acorns.

Fleshy fruits

In fleshy fruits, at least part of the mesocarp is soft or fleshy when the fruit is ripe. These types of fruits tend to be the ones that most people recognize as fruits. *Simple fleshy fruits* form from flowers that have one pistil with either a simple or compound ovary.

- ***Drupes* are fleshy fruits with a single seed protected by a hard, stony endocarp called a *pit*.** Anytime you've eaten a peach or plum, you've eaten a drupe. Coconuts are an unusual example of a drupe — the husk that many people never see is the exocarp and mesocarp of the fruit. The coconuts sold in stores are just the pit of the coconut fruit with the hard endocarp and seed within.
- ***Berries* usually develop from compound ovaries and contain multiple seeds.** The endocarp of berries is fleshy like the rest of the pericarp, so it's difficult to tell this layer from the rest. *True berries,* such as tomatoes, grapes, and peppers, have a thin skin and are soft when ripe. *Pepos* are berries with a thick skin, or *rind,* as in pumpkins and other squash. Oranges, lemons, and other citrus fruits are a type of berry called a *hesperidium* that has a leathery, oily skin.
- ***Pomes* form when the fruit receptacle enlarges and grows up around the ovary, becoming part of the fruit.** The endocarp of pomes forms a papery or leathery layer around the seeds. Apples are probably the most familiar pomes. In apples, the ovary itself becomes the core of the apple, while the rest of the apple develops from the receptacle.

TECHNICAL STUFF

Botanists also call fruits like apples *accessory fruits* because part of the fruit develops from a part of the flower other than the ovary itself.

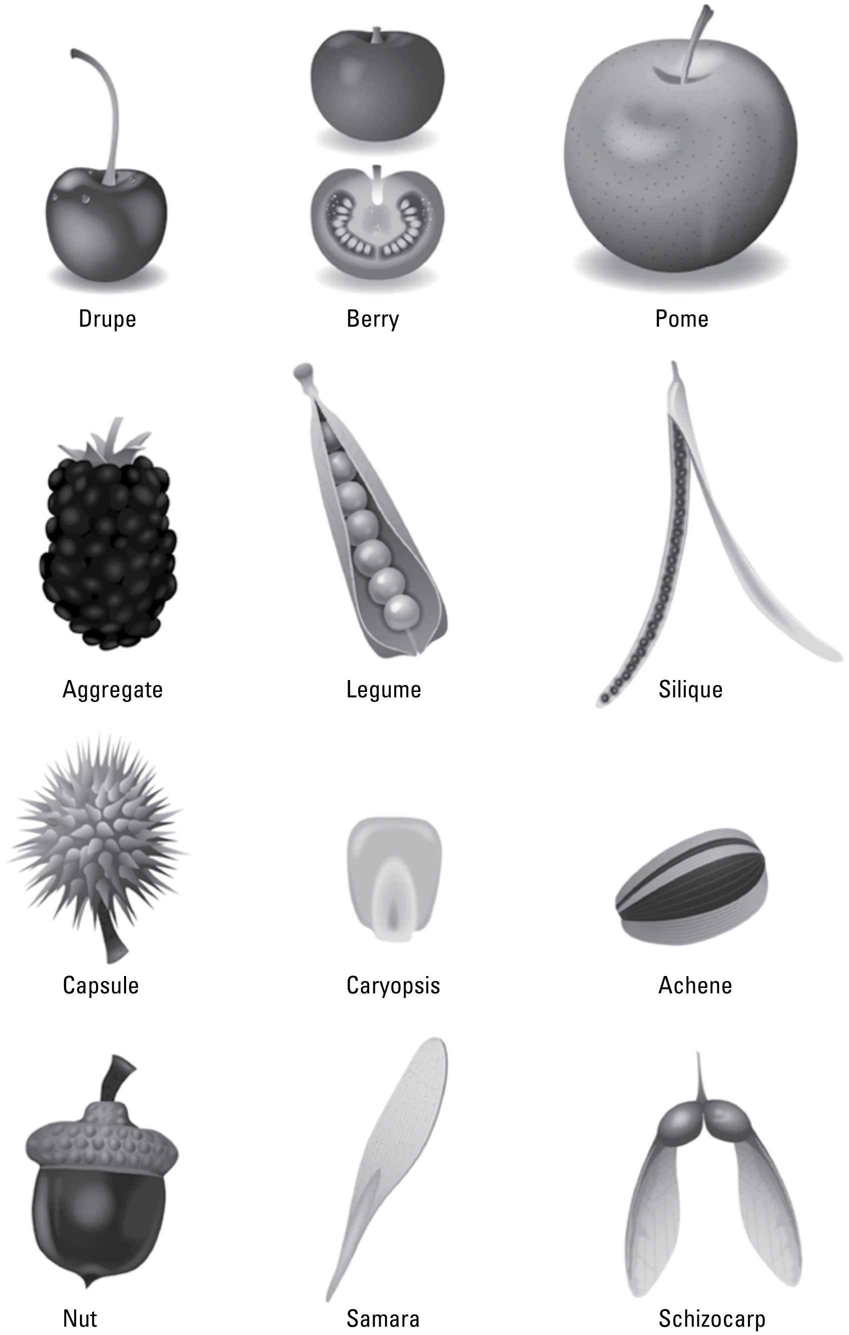

Drupe
Berry
Pome
Aggregate
Legume
Silique
Capsule
Caryopsis
Achene
Nut
Samara
Schizocarp

FIGURE 4-7: Types of fruits.

Aggregate fruits

Aggregate fruits form from single flowers that have multiple pistils. Each pistil develops into a *fruitlet*, and all the fruitlets are clustered together on a single receptacle. Raspberries, blackberries, and strawberries are all aggregate fruits (and not really berries at all!). The part of the strawberry that gets red and juicy is actually its swollen receptacle, and the little hard seed-like things on the outside are little fruitlets called *achenes*. Because the receptacle forms part of the fruit, botanists call it *accessory tissue*.

Multiple fruits

Multiple fruits develop from multiple flowers in a single inflorescence. The ovaries of the individual flowers develop into fruitlets that grow together to form one, larger fruit. Pineapples are an example of a multiple fruit — each little diamond-shaped section that you see on the outside of a pineapple represents one of the original flowers in the inflorescence. All the fruitlets fused together to form the larger pineapple.

Dry fruits

Dry fruits have a dry mesocarp when the fruit is mature. Some dry fruits, called *dehiscent fruits*, split open when they're ripe, releasing the seeds. Other dry fruits, called *indehiscent fruits*, stay intact. Because dry fruits may remain intact near a plant even when there are no flowers, recognizing the different types of dry fruits is another helpful clue when you're trying to identify a plant.

Botanists group *dehiscent fruits* according to the way they open:

- ***Follicles* split open along one side of the fruit.** Butterfly weed (such as the one in Figure 4-8), columbines, and peonies all produce follicles.
- ***Legumes* split open along two sides.** Beans, peas, carob, and mesquite all produce legumes.
- ***Siliques* also split open along two sides, but the seeds initially stay attached to a central partition inside the fruit.** Siliques tend to be long and thin. Fruits that open the same way as siliques, but are shorter and wider, are called *silicles*. Silicles and siliques are made by plants in the mustard family, such as broccoli, radishes, and cabbage. One mustard is often called money plant because its silicles look like coins.

- **Capsules can split open in a number of different ways.** Some capsules, like those of iris plants, split open along the partitions between the chambers of the ovary. Others form a cap at one end that may pop off to release the seeds. The capsule of poppy flowers, such as the one shown in Figure 4-8, develops holes in the cap through which the seeds can be shaken out.

Botanists group *indehiscent fruits* according to the degree of attachment between the seed and the pericarp and the structure of the pericarp:

- ***Achenes* have seeds that are attached to the pericarp only at the base.** Sunflowers produce achenes. Because the seeds are attached to the husk at only one point, it's relatively easy to pry the seeds out and eat them.
- ***Nuts* have one seed, but they are larger than achenes, and they have a thick, hard pericarp as well as a protective husk.** In the Oak family, the nuts have a cup or cluster of bracts at their base, like you see on an acorn.

  WARNING

  Many foods that people commonly call nuts, aren't really nuts — botanically speaking. Peanuts are legumes; almonds, cashews, pistachios, and macadamia nuts come from drupes; and Brazil nuts are seeds from a capsule.
- ***Grains* or *caryopses* have seeds that are tightly joined to the pericarp so that they can't be separated from each other.** All members of the grass family, including wheat, corn, barley, rice, and oats, make grains.
- **In *samaras,* the pericarp forms wings that extend out from the seeds.** The winged fruits of maple trees are a common example of samaras.
- ***Schizocarps* split into two halves when they are mature, but the seeds remain inside the fruit.** Carrots, dill, and caraway all make schizocarps.

Dispersing Fruits and Seeds

For organisms that can't get up and move around, plants sure seem to get around. Plants have successfully managed to spread themselves over most of the land on planet earth, without ever moving a muscle. Instead, they've evolved many clever strategies for using the resources available to them — wind, water, and animals — to cast their seeds far and wide.

Figure 4-8 summarizes the strategies used by plants to disperse their fruits and seeds:

- **Wind dispersal:** Winged maple seeds spin like helicopters in the breeze, and dandelion fruitlets use plumes like little parachutes to carry themselves far and wide. Plants that use wind dispersal produce light fruits or seeds that may have attachments like wings or hairs to help give them lift.
- **Animal dispersal:** Prickles and burrs and poop, oh my! Some fruits and seeds, such as those of bedstraw and cockleburs, have spines or thorns that catch in animal fur or on hikers' socks, so the plant can hitch a ride to a new location. Other plants make fleshy fruits with seeds that can pass safely through an animal's digestive system. Animals eat the fruit and then spread the seeds around later after digestion.
- **Mechanical dispersal:** Instead of relying upon wind, some plants build explosive mechanisms into their fruits. When witch hazel capsules dry, they split in a way that flings the seeds far from the parent plant. A simple touch will cause the swollen capsules of a type of *Impatiens* called touch-me-nots to explode, helping the plants to disperse their seeds and providing amusement for hikers at the same time.
- **Water dispersal:** Some plants have seeds with waxy coatings or attached sacs of air that help the seeds float so that they can be dispersed by water. Coconuts float in the ocean, dispersing themselves to new tropical islands.

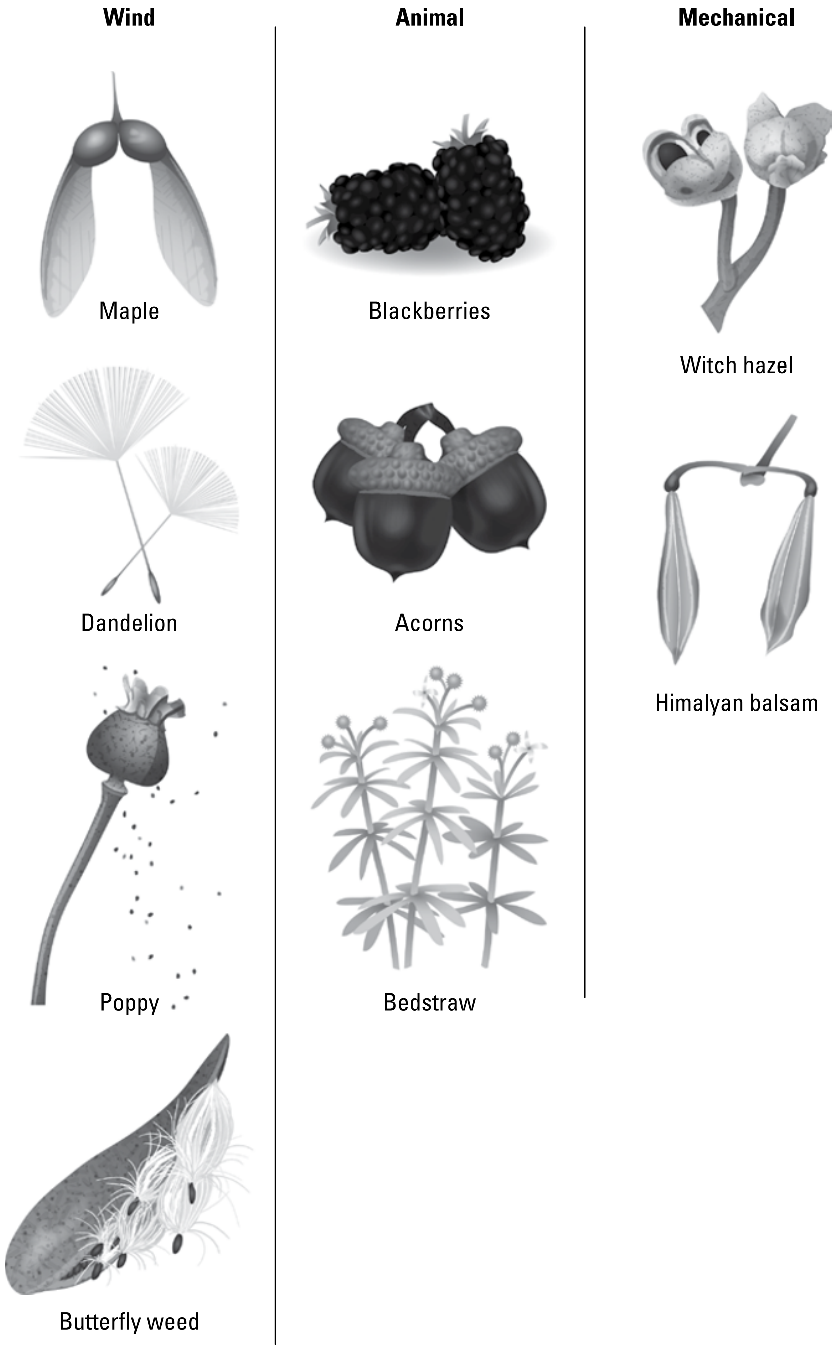

Wind
Animal
Mechanical
Maple
Blackberries
Witch hazel
Dandelion
Acorns
Himalyan balsam
Poppy
Bedstraw
Butterfly weed

FIGURE 4-8: Fruit and seed dispersal.

2

Discovering Plant Physiology

IN THIS PART . . .

Find out what is and isn’t food for plants

Explore photosynthesis, the process that plants use to get the matter and energy they need to grow

Discover that, just like you, plants have mitochondria that they use to extract energy from food

Peer into the plumbing of plants and see how they move water from the roots to the leaves and sugars from the leaves to the roots

Get acquainted with the signals plants use to regulate their growth and development

IN THIS CHAPTER

- Discovering the real reason soil is good for plants
- Figuring out how to capture energy from the sun
- Comparing noncyclic and cyclic photophosphorylation
- Exploring the details of carbon fixation

Chapter 5

Photosynthesis: Making Sugar from Scratch

Cells that do photosynthesis have been providing food for life on earth for hundreds of millions of years. During photosynthesis, cells use energy from the sun to make carbohydrates from carbon dioxide. The overall process can be broken down into two major steps, called the light reactions and the light-independent reactions. In this chapter, I present an overview of photosynthesis that looks at its importance to life as well as the details of the reactions themselves.

Rethinking the Role of Soil

In order for you to understand photosynthesis, the first thing you need to do is examine what you think you already know about plants and make sure that you're not stuck on a very common misunderstanding.

WARNING

The most common wrong idea that people have about plants is that they grow by taking matter from the soil. On the surface, this idea seems reasonable. If you look at plants, you see them getting bigger without eating, and their only connection with anything solid appears to be their roots stuck in the ground.

But the power of science lies in taking a closer look at the natural world and carefully testing people's ideas about it. And guess what? When you take a really close look at how plants grow, you find out that it's not really about soil. Yes, plants take water and minerals from the soil, but that's not where they get most of the stuff that makes up the body of the plant. The raw material for building most of the plant body comes from carbon dioxide that plants take in through the stomata in their leaves!

This concept is hard for many people to believe because air seems like nothing, and how could a plant grow from nothing? But air isn't really nothing; it's a mixture of gases. And gases are something. For example, think about steam, which scientists call water vapor. It's water in gas form. If you cool steam, it becomes liquid water, and if you freeze it, it becomes solid ice. Likewise, carbon dioxide, which seems like nothing, can be cooled down to form a solid that people call dry ice. Or, if you're a plant, you can take gaseous carbon dioxide into your leaves and use photosynthesis to rebuild the atoms in the carbon dioxide into carbohydrates. It's almost like plants use photosynthesis to make something from "nothing."

van Helmont's experiment

One of the first scientists who investigated the idea that plants take something from the soil was a Belgian doctor named Jean Baptiste van Helmont. In 1642, van Helmont did one of the most famous experiments ever done with plants.

Here are the basics of van Helmont's experiment:

1. **He dried soil in an oven to make sure that it didn't contain any water and then placed 200 pounds of soil in a pot.**
2. **He planted a young willow tree, which weighed 5 pounds, in the pot and moistened the soil with rain water.**
3. **He grew the tree for five years, watering it with rain water or distilled water whenever necessary.**
4. **At the end of the five years, he removed the tree from the pot and weighed it again.**

   At the end of the experiment, the tree weighed 169 pounds, 3 ounces.
5. **He removed the soil from the pot, dried it, and reweighed it.**

   After five years, during which the tree gained 164 pounds, the soil only lost 2 ounces of its weight!

This experiment is famous today because it shows clearly what is so hard for people to believe: Plants grow and gain weight while taking hardly anything at all from the soil! At the time, van Helmont thought the mass of the tree must come from water, but now we know that plants are made of carbohydrates, proteins, nucleic acids (like DNA), and lipids (like fats and oils), all of which are carbon-based molecules. So, plants can't possibly grow by water alone; they need a source of carbon which is where carbon dioxide comes into the picture.

The real role of soil

At this point, you may be wondering why plants need soil at all. The answer is they don't, really. That's what *hydroponics*, growing plants in a solution of water and minerals, is all about. But notice that hydroponics includes minerals in with the water. That's the key to what soil really provides to plants. Soil to a plant is a lot like a vitamin tablet to a person — it provides small amounts of chemicals that help the plant grow, but that don't provide the building blocks necessary to build the plant body.

Just like you need food to build and maintain your tissues, plants need food to build and maintain theirs. The difference between you and a plant is that you have to eat other organisms to get your food, but plants can make their own. If you imagine all the food you eat in a day compared to one small vitamin tablet, that might give you an idea of the relative contribution of food vs. minerals from the soil to a plant: Their bodies are built mostly from food they make, with just a small amount of minerals from the soil added in.

REMEMBER

Plants use soil as a source of inorganic compounds called *minerals* and as a matrix in which to grow. Plants get 13 mineral nutrients from the soil. These nutrients can be divided into two categories based on how much plants need:

- ***Macronutrients* are needed in relatively large amounts:**
  - **Plants need nitrogen (N), phosphorous (P),** and **sulfur (S)** for the construction of molecules other than carbohydrates. For example, proteins contain large amounts of nitrogen and small amounts of sulfur. If a plant cell needs to build proteins, it takes some of its stored carbohydrates (which contain carbon (C), hydrogen (H), and oxygen (O), adds nitrogen and sulfur from the soil, and rearranges the atoms to form a protein. Similarly, plants can build DNA, which contain phosphorous and nitrogen, by combining these elements with those from their stored carbohydrates.
  - **Plants need potassium (K), calcium (Ca),** and **magnesium (Mg)** as helpers called *cofactors* for their enzymes. Cofactors partner with enzymes to catalyze certain reactions. If enzymes don't have their cofactors, they won't work properly and a metabolic pathway will shut down, causing the plant to grow abnormally.

- **Plants need *micronutrients* (or *trace elements*) in very small amounts.** Boron (B), copper (Cu), iron (Fe), chloride (Cl), manganese (Mn), molybdenum (Mo), and zinc (Zn) also act as cofactors for plant enzymes.

TIP

You can remember the macronutrients needed by plants with the phrase "C. Hopkins café, mighty good!", which is how you read this sentence: CHOPKNS CaFe Mg. C, H, and O stand for carbon, hydrogen, and oxygen, which are the three nonmineral macronutrients needed by plants (and which they get from photosynthesis!). P, K, N, and S are phosphorous, potassium, nitrogen, and sulfur, while Ca stands for calcium, Fe is iron (a micronutrient), and Mg is magnesium.

Soil helps plants grow better because it provides the minerals they need to make molecules that contain elements besides the *nonmineral nutrients*, carbon, hydrogen, and oxygen. Because minerals are also required for optimal enzyme function, you get the best plant growth from soil that is very rich in minerals. To ensure the best growth, people often add chemical fertilizers that contain minerals to the soil. In particular, fertilizers usually contain a great deal of nitrogen and phosphorous, which are the two elements that plants use up most quickly from the soil.

WARNING

Some fertilizers are called plant food, but they're not really food! They contain minerals like nitrogen and phosphorous that plants tend to use up quickly from the soil. Someone thought "plant food" sounded better than "plant fertilizer," but the only real plant food is the carbohydrates they make for themselves.

Discovering Photosynthesis Fundamentals

REMEMBER

Photosynthesis transforms light energy into chemical energy that is usable by living things. Plants capture the energy from the sun and store it in the bonds of carbohydrates (such as glucose or G3P, which stands for glyceraldehyde-3-phosphate) they make from carbon dioxide (CO_2) and water (H_2O). With these carbohydrates and some minerals, plants can build all the molecules needed for life: proteins, carbohydrates, lipids, and nucleic acids. Plants also make oxygen gas (O_2) as a waste product during photosynthesis.

Photosynthesis is summarized by the following chemical reaction:

$$6CO_2 + 6H_2O + \text{ light energy } \rightarrow C_6H_{12}O_6 + 6O_2$$

This reaction summarizes all the events of photosynthesis into one chemical sentence with reactants (inputs) on the left side of the arrow and products (outputs) on the right side of the arrow.

The summary reaction is useful for thinking about the big picture the matter and energy transfers that occur during photosynthesis:

- **Plants transfer matter from the environment into matter inside the plant body.** Plants capture CO_2 from the air and H_2O from the soil and then rearrange the bonds between the carbon, hydrogen, and oxygen atoms, ultimately forming the carbohydrate glucose ($C_6H_{12}O_6$) and the waste O_2. The glucose is used as building material and energy storage inside the plant and the oxygen is released back to the environment.
- **Light energy from the sun is transformed into chemical energy and stored in the bonds of sugar for later use by the plant.** Plants use cellular respiration to break down the sugars, transferring the energy to an energy carrier molecule called *ATP*, which stands for *adenosine triphosphate*. (For more on cellular respiration, see Chapter 6.)

TIP

You can think of ATP as a rechargeable battery. Cells use ATP to provide the energy they need for cellular processes like growth, repair, and movement. Cells transfer energy from ATP to a cellular process by removing one of its three phosphate groups and loaning it to another molecule. This converts ATP to ADP (adenosine diphosphate). ADP has less stored energy than ATP, so it is like a battery that is low on power. Cells transfer energy from the sun or food to charge ADP back to ATP (by reattaching a phosphate).

REMEMBER

The overall purpose of photosynthesis is to combine matter and energy into food in the form of carbohydrates.

TIP

As an analogy, compare a baker making a cake to a plant doing photosynthesis. A baker puts the cake's building blocks, such as eggs, flour, and milk, into a bowl. A plant brings matter in the form of carbon dioxide (CO_2) and water (H_2O) into its cells. The eggs, flour, and milk contain all the necessary ingredients to make the cake, but at this point, they don't look much like a cake. Similarly, the CO_2 and H_2O contain the carbon, hydrogen, and oxygen atoms that are needed to build carbohydrates ($C_6H_{12}O_6$), but they're not yet in the right arrangement. In order to create the changes they want in the cake, the baker places it into the oven. The heat energy from the oven helps the cake batter change. Likewise, plants absorb light energy from the sun and use it to power a series of reactions that build $C_6H_{12}O_6$ from CO_2 and H_2O. Like the heat from the oven, the light from the sun provides the energy to change the raw materials of CO_2 and H_2O into something different — carbohydrates!

Going solar

As people today wrestle with the energy crisis brought on by declining fossil fuels, they're considering alternative energy sources like the sun, an energy source that plants have been relying on for 500 million years. The sun is basically a giant nuclear reactor positioned at a safe distance from the earth. Nuclear fusion inside the sun produces a mind-boggling amount of energy in the form of *electromagnetic radiation* that includes visible light, X-rays, microwaves, and ultraviolet radiation (see Figure 5-1). Plants capture electromagnetic radiation within the visible light band for photosynthesis.

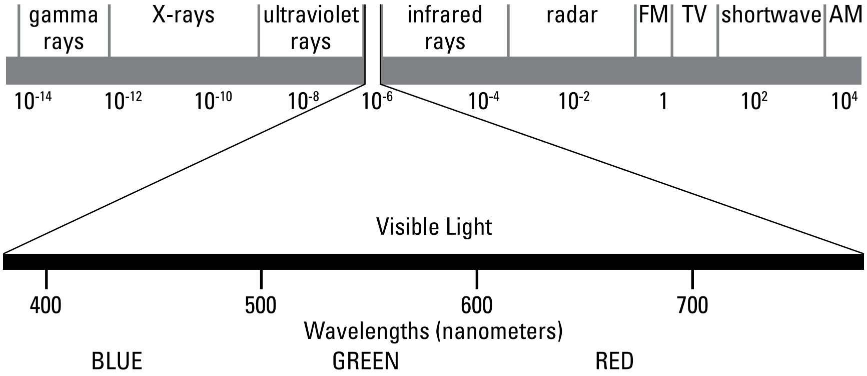


FIGURE 5-1: The electromagnetic spectrum.

Electromagnetic radiation travels from the sun to the earth in waves. Each type of electromagnetic energy is identified by its *wavelength*, the distance from one energy peak to another. The shorter the wavelength, the more energy in the wave. Gamma rays have the shortest, highest energy wavelengths, while radio waves have the longest, lowest energy wavelengths. Energy waves are measured in nanometers (nm). Each nm is only 1 / 1,000,000,000 of a meter, so wavelengths of light are pretty small! Plants capture wavelengths between 400 and 700 nanometers for photosynthesis. Radiation with wavelengths of 400 nanometers is visible as blue light, while radiation with wavelengths around 700 nanometers are visible as red light.

REMEMBER

Plants primarily absorb red and blue light for photosynthesis

Catching some rays with pigments

REMEMBER

Plants appear colored because of their *pigments*, colored molecules that absorb light. The most abundant pigment in plants is *chlorophyll*, which gives plants their green color. Chlorophyll is abundant in plant leaves, where it absorbs light to provide energy for photosynthesis. Chlorophyll appears green because it absorbs blue and red light (see Figure 5-2), but doesn't absorb green light. Green light hits the leaves of the plant and bounces off again, traveling to your eye and causing your brain to interpret the color as green. So, green plants appear green because of their chlorophyll.

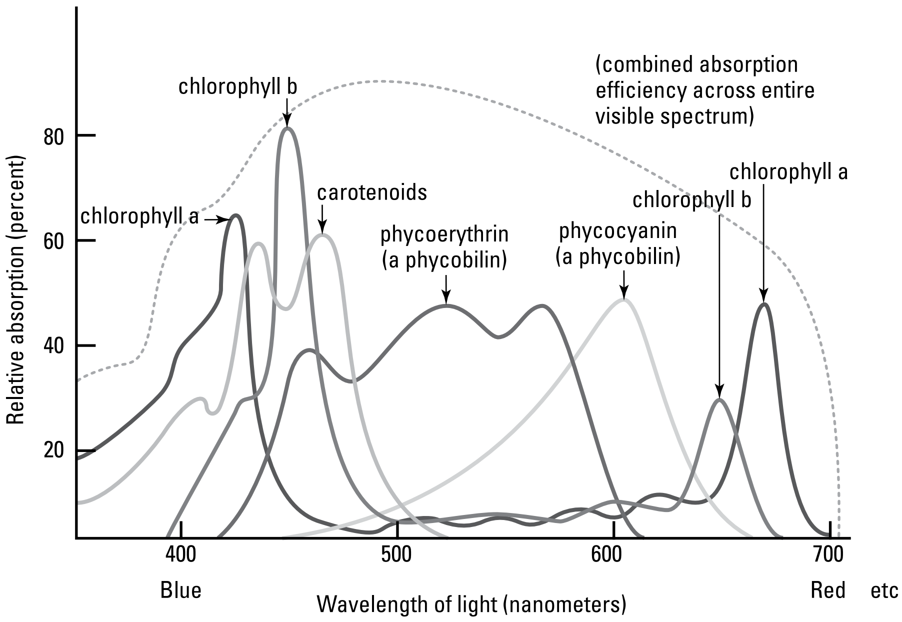


FIGURE 5-2: Absorption spectra for photosynthetic pigments.

Photosynthetic organisms, such as plants, algae, and some bacteria, contain several types of chlorophyll as well as other pigments. The different types of chlorophyll molecules are all similar in structure, each containing an atom of magnesium (Mg) and long lipid tails that anchor them into the thylakoid membrane of the chloroplast.

The structure of each pigment type determines what kind of light they can absorb (see Figure 5-2):

- Plants, algae, and cyanobacteria (blue-green bacteria) all contain *chlorophyll a,* which absorbs blue and red light and looks blue-green to the human eye.
- Plants and green algae also contain *chlorophyll b,* which absorbs slightly different blue and red wavelengths than chlorophyll a and looks more grass green.
- Brown algae make *chlorophyll c,* which absorbs blue and red and looks green.

- Bacteria other than cyanobacteria produce *bacteriochlorophyll,* which absorbs blue and red and looks very similar to chlorophyll *a.*
- Plants, algae, and photosynthetic bacteria also contain orange-red pigments called *carotenoids.* Several different pigments, including carotene and fucoxanthin, are in this group. The carotenes in this group absorb blue and look orange. (In which vegetable would you find a lot of these orange-colored pigments? If you said carrots, you're right!) Fucoxanthins absorb green and look yellow-brown. Next time you go to the beach, look for the brownish colored seaweed on the rocks. You'll know that they have fucoxanthin to help them absorb light energy!
- Cyanobacteria and red algae get their colors from *phycobilins*. Phycobilins come in two kinds: *phycocyanin* and *phycoerythrin*. Phycocyanin absorbs in the red and looks blue, giving cyanobacteria their characteristic blue-green color. Phycoerythrin absorbs in the green and looks red. Reddish-colored seaweeds have lots of phycoerythrin.

REMEMBER

By having chlorophyll a, plus these other accessory pigments, photosynthetic organisms increase the wavelengths of light energy they can absorb for use in photosynthesis. The dashed line in Figure 5-2 shows all the kinds of light a plant could absorb if it could make all the different types of photosynthetic pigments.

If you've ever admired the changing colors of leaves in the fall, you were observing the beauty of accessory pigments. Leaves always contain accessory pigments, but during the growing season they contain so much chlorophyll that the green color hides the other pigments. As nights get longer in temperate regions, some plants get ready to drop their leaves. One way these deciduous plants get ready is by slowing down chlorophyll production. Existing chlorophyll molecules break down, and with less being made, the green color of the leaves fade, revealing the accessory pigments in a bright blaze or oranges, yellows, and reds.

Connections between the light and light-independent reactions

Plants use their pigments to capture energy from the sun, ultimately using that energy to transfer electrons from water to carbon dioxide in order to make sugars. Water gives up its electrons as part of hydrogen atoms, leaving behind oxygen atoms that form gaseous oxygen, which is why plants produce the oxygen that you breathe.

REMEMBER

During the process of photosynthesis, water is oxidized (gives up electrons), and carbon dioxide is reduced (gains electrons, see Figure 5-3).

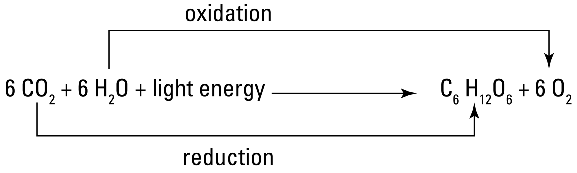


FIGURE 5-3: Oxidation and reduction during photosynthesis.

The summary reaction for photosynthesis, shown in Figure 5-3, is a good reminder of the overall purpose of photosynthesis in other words, the "why" of photosynthesis:

- Plants capture matter (carbon dioxide and water) and energy (light) from the environment and combine them to produce food in the form of carbohydrates (glucose).
- As a waste product of photosynthesis, plants release oxygen back to the environment.

Photosynthesis gets more complicated when you tackle the process itself — in other words, the "how." Photosynthesis doesn't occur in one step as indicated by the summary reaction. Instead, it's broken up into lots of little steps, which are organized into two separate sets of reactions, called the *light reactions* and the *light-independent reactions* that occur in different parts of the chloroplast. Figure 5-4 presents an overview of the two parts of photosynthesis and shows how they're connected.

TIP

In this book, I refer to the two main phases of photosynthesis as the *light reactions* and the *light-independent reactions.* The light reactions require light in order to occur, whereas the light-independent reactions require no light at all. Some botanists refer to these phases using other terms: The light reactions are also called the light-dependent reactions. The light-independent reactions are also called the *Calvin-Benson cycle*, the *Calvin cycle*, and the *dark reactions*.

Each part of photosynthesis has a separate purpose, but they both contribute to the overall goal of storing matter and energy in sugar molecules:

- **In the light reactions, plants capture light energy from the sun and transform it into chemical energy**. The energy from light is transformed to chemical energy as it's stored in the energy molecule ATP. During the light reactions, plants also take electrons from H_2O and transfer them to the electron carrier NADPH.
- **In the light-independent reactions, plants capture carbon dioxide (CO_2) and convert it into carbohydrates.** In this process, plants use electrons from NADPH and energy from ATP to reduce the CO_2 and convert it to a sugar.

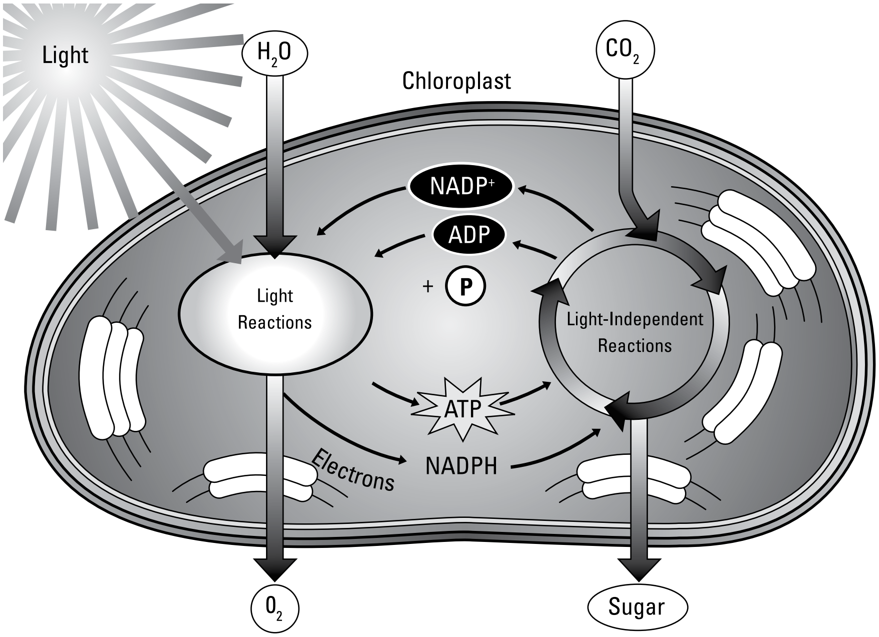


FIGURE 5-4: The two halves of photosynthesis, the light reactions and the light-independent reactions, are separate but linked.

REMEMBER

Plants make ATP and NADPH during the light reactions and then use these molecules during the light-independent reactions to make carbohydrates from CO_2.

TIP

Living things transfer and transform energy all the time. When organisms *transfer* energy, they move it from one place to another. If you eat some noodles, you transfer chemical energy from the noodles to chemical energy in your own cells. When organisms *transform* energy, they change it from one type of energy to another. During photosynthesis, plants capture energy from the sun, which is light energy and transform it into chemical energy in their cells. (Photosynthesis is actually a double whammy — plants transform light energy to chemical energy, and they also transfer the energy from the sun to their own cells!)

TIP

To understand the role of electrons and NADPH in the process of photosynthesis, compare the chemical formula for carbon dioxide (CO_2) and the carbohydrate glucose ($C_6H_{12}O_6$). If you want to turn CO_2 into $C_6H_{12}O_6$, what do you need? In other words, what is missing from CO_2? What is missing is hydrogen (H), which is what NADPH provides to the process of sugar construction during the light-independent reactions. Essentially, this hydrogen is taken from water (H_2O) during the light reactions and carried by NADPH to the light-independent reactions. NADPH donates the H needed to build $C_6H_{12}O_6$ out of CO_2. (Each H atom contains one electron, so when NADPH donates an H, it is also donating an electron to, or *reducing*, the CO_2.)

Harnessing the Sun: The Light Reactions

The sun releases mind-boggling amounts of energy, absolutely free for the taking, every second of every day. To put the amount of available energy in terms that you can probably relate to, 400 trillion trillion watts of energy reach the earth's surface every second. In one second, that's enough energy to power current human civilizations for 500,000 years. If people tapped into that energy the way that plants do, society wouldn't need fossil fuels at all!

Living cells have been capturing the sun's energy for over 3,000 million years. Bacteria invented photosynthesis, at first using a cyclic set of reactions that didn't produce oxygen. Then cyanobacteria started using water as their electron source about 2,500 million years ago, releasing the first oxygen into the earth's atmosphere. (Imagine that! The very atmosphere of the earth is the way it is today because of photosynthesis!) Eukaryotic photosynthesis performed by the world's first algae probably began about 1,500 million years ago. So, for all these thousands of millions of years, life on earth has relied upon photosynthesis to create the food upon which all living things rely.

Transferring light energy to chemical energy with electron transport chains

Plants absorb light energy and convert it to chemical energy using *electron transport chains*, a series of large proteins stuck in a membrane that pass electrons along the chain like runners in a relay race pass a baton. During photosynthesis, plants use electron transport chains in the thylakoid membranes inside their chloroplasts. When light energy excites the chlorophyll molecules in the chain, electrons start moving from one protein to another. Cells use the movement of electrons through the chain to transfer energy. In the case of the light reactions, energy is transferred from sunlight to ATP. Figure 5-5 shows the electron transport chain plants use during the light reactions of photosynthesis.

TIP

If you think of ATP as a rechargeable battery, then electron transport chains are the battery chargers. During the light reactions, light energizes the battery charger so it can transfer energy into the ATP molecules.

COPYCAT SCIENTISTS

You might be wondering if photosynthesis is so fabulous and has worked amazingly well for thousands of millions of years, why can't people copy the process to solve energy needs? The good news is that people probably can, and scientists are trying. Photovoltaic cells, the light-harvesting part of solar panels, have been in use since the 1950s. Each cell contains a material that absorbs light, causing it to release electrons and create a current. Plants essentially do the same thing during photosynthesis: Chlorophyll absorbs light and then releases electrons to a series of proteins. Most photovoltaic cells in use today rely on silicon-based materials to absorb the light energy. A couple of problems with silicon-based photovoltaic cells are that they're expensive to manufacture and don't perform well on cloudy days.

Recently, scientists in New Zealand have experimented with replacing the silicon-based materials with synthetic dyes, including synthetic chlorophyll! The dyes are cheaper to manufacture than the silicon-based materials and work well in low light, similar to those on cloudy days. Other researchers at the Massachusetts Institute of Technology aren't just copying chlorophyll; they're trying to copy the process of the light reactions. The MIT scientists coated viruses with light-harvesting pigments and then set up a system where the viruses would absorb light energy and interact with catalysts to trigger the splitting of water. The scientists hope to store hydrogen gas from this reaction and develop its use an alternative fuel. Many more groups of scientists around the world are looking to plants for ideas on how to capture sunlight. The future is looking green in more ways than one!

Transferring light energy

Plants maximize their ability to capture light energy by using *accessory pigments* along with chlorophyll. Plants combine these pigments, along with other proteins, to form large complexes called *photosystems* that are part of the electron transport chains in the thylakoid membranes. Each photosystem contains a special molecule of chlorophyll *a* that forms the *reaction center*, the place where light energy is transferred to the electron transport system. Other molecules of chlorophyll *a*, chlorophyll *b*, and carotenoids surround the reaction center chlorophyll. The pigments that surround the reaction center form an *antenna complex* that absorbs light energy and transfers it into these reaction centers.

REMEMBER

When the reaction center chlorophyll receives light energy, its electrons are excited to a higher energy state, causing them to move first to outer electron orbitals and then jump to a protein in the electron transport chain.

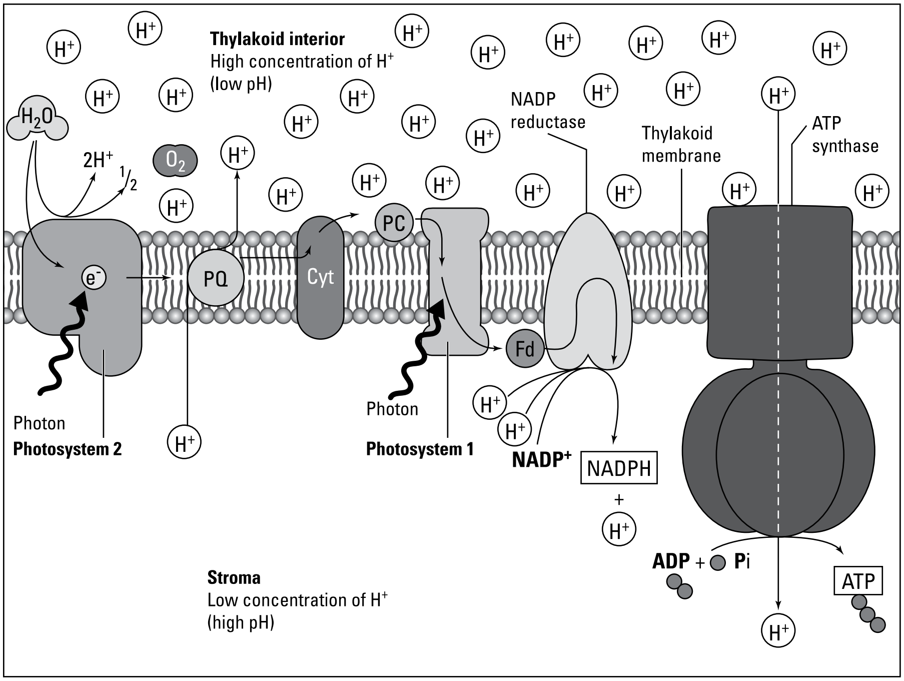

H⁺
Thylakoid interior
High concentration of H⁺
(low pH)
H₂O
2H⁺
½
O₂
NADP reductase
Thylakoid membrane
ATP synthase
e⁻
PQ
Cyt
PC
Fd
Photon
Photosystem 2
Photon
Photosystem 1
NADP⁺
NADPH
+
ADP + Pi
ATP
Stroma
Low concentration of H⁺
(high pH)

FIGURE 5-5: The light reactions of photosynthesis (noncyclic photophosphorylation) in a thylakoid membrane.

TIP

When energy flows from the antenna complex to the reaction center chlorophyll, it's a little bit like people "doing the wave" at a sporting event. Imagine yourself as the reaction center chlorophyll. Light energy is absorbed by the other pigments, causing them to be energized like a line of people standing up to do the wave. The wave travels nearer and nearer to you and then arrives at your location. You're excited and jump up to do the wave! Lifting your arms is like your electrons moving to a higher orbital. If you were the reaction center chlorophyll, you'd then pass one of these electrons to the electron transport chain.

REMEMBER

When the excited electron from chlorophyll is transferred to the electron transport chain, the plant cell has successfully transferred light energy to chemical energy!

Electron transport chains

Electron transport chains accept electrons from an electron donor, pass them along through the protein complexes in the chain, and then pass them to a final electron acceptor.

At the same time the reaction center chlorophyll donates an electron to an electron transport chain in the thylakoid membrane, water molecules are split and electrons from water replace the electrons lost from the reaction center chlorophyll. Water is the electron donor to the electron transport chains during the light reactions.

Electrons move from chlorophyll to the next protein complex in the electron transport chain, which then gives them up to the third complex in the chain. Complexes are temporarily reduced when they accept electrons and then become oxidized again when they give those electrons up to the next member of the chain. So, as the electrons move along the chain, a series of redox reactions occurs. The electrons move from complex to complex along the chain because each member of the chain is more *electronegative*, or has more pull for electrons, than the complex before it. Electrons continue to move through the electron transport chain until they're transferred to the electron carrier $NADP^+$, which is reduced to $NADPH + H^+$.

TIP

You can think of the protein complexes in an electron transport chain as a bunch of kids who all want the same piece of candy (the electrons). A little kid is holding the candy. Only a stronger kid (more electronegative) can pull the candy away from the little kid. Then, an even stronger kid can pull the candy away from the second kid, and so on. In this analogy, the kid who ends up with the candy will be the strongest kid of all.

REMEMBER

$NADP^+$ is the *final electron acceptor* during the light reactions.

Making ATP by chemiosmosis

Plants use pigments to absorb light energy and then transfer that energy to ATP by a process called *chemiosmosis.* Chemiosmosis uses electron flow through an electron transport chain, coupled with the transport of hydrogen ions (H^+) across a membrane to transfer energy to ATP.

The steps of chemiosmosis are

1. **Electrons move from protein to protein in an electron transport chain.**
2. **Some proteins in the chain transfer energy from the movement of electrons to help them pump hydrogen ions (H^+) across the membrane.**
3. **The hydrogen ions move back across the membrane through a protein called *ATP synthase,* which can catalyze the formation of ATP.**
4. **ATP synthase transfers energy from the movement of H^+ into the formation of ATP.**

TIP

To understand chemiosmosis, think about how people use dams to generate hydroelectric power. Water trapped behind the dam is like the H^+ trapped behind a membrane. Both represent stored energy. When water crosses the dam through a turbine, the turbine spins, creating electrical current. When H^+ flows through ATP synthase, the protein actually spins, too! And just like electrical current powers your home, the flow of H^+ through ATP synthase powers the synthesis of ATP.

REMEMBER

When plant cells use light energy and electron transport chains to make ATP, it's also called *photophosphorylation*. *Photo-* refers to the light energy that's being used, and *phosphorylation* means adding a phosphate to something. In this case, plants cells are adding a phosphate to ADP, which is the building block for ATP. So photophosphorylation literally means "making ATP using light," which is really just another way of saying "the light reactions of photosynthesis."

Noncyclic and cyclic photophosphorylation

Two different types of photophosphorylation occur in plant and other photosynthetic cells:

- **During *noncyclic photophosphorylation*, electrons from water (H_2O) move through an electron transport chain to the electron carrier NADPH.** In other words, the electrons take a one-way journey from water to NADPH. Noncyclic photophosphorylation occurs in plants, algae (seaweed), and cyanobacteria (blue-green bacteria). It's also called the *Z-scheme* because a graph of the energy changes in the electrons as they move through the electron transport chain look like the letter Z (see Figure 5-6). Noncyclic photophosphorylation requires both Photosystem II and Photosystem I. Photosystem II comes before Photosystem I in the Z-scheme.
- **During *cyclic photophosphorylation*, electrons leave chlorophyll when they get excited, travel through an electron transport chain, and return to chlorophyll after their energy has been transferred to ATP.** In other words, the electrons take a round-trip journey from chlorophyll to an electron transport chain and then back to chlorophyll. In plants, algae, and cyanobacteria, cyclic photophosphorylation occurs along with noncyclic photophosphorylation. Bacteria other than cyanobacteria just use cyclic photophosphorylation, which only requires Photosystem I.

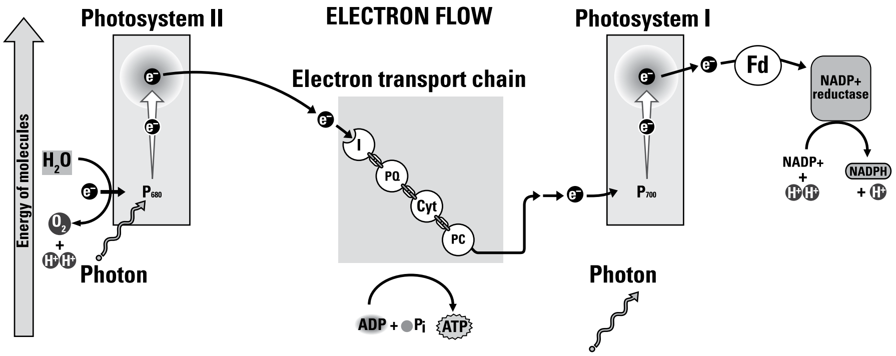


FIGURE 5-6: The Z scheme (noncyclic photophosphorylation).

TIP

Photosystem I and Photosystem II were named for the order in which they were discovered, not for the order in which they appear in the Z scheme. That's why the numbering seems backward in the Z-scheme.

The steps of noncyclic photophosphorylation

During noncyclic photophosphorylation, both photosystems absorb light energy and transfer it to an electron transport chain that's used to make ATP and NADPH. As you read the steps of noncyclic photophosphorylation, refer to Figure 5-6:

1. **Photosystem II absorbs light energy.**

   The accessory pigments transfer light energy to the reaction center chlorophyll, exciting its electrons.

2. **Excited electrons leave the reaction center chlorophyll and move to the electron transport chain.**

   The electrons first pass to *pheophytin,* a molecule similar to chlorophyll, and then to plastoquinone (PQ). Plastoquinone transfers the electrons to an electron transport chain that contains *cytochromes* (cyt), iron- containing proteins that are good at transporting electrons.

3. **The light energy absorbed by Photosystem II also splits a water molecule in a process called photolysis.**

   Electrons from water replace the electrons lost by chlorophyll in Photosystem II. Plants release the oxygen left over from the split water molecules to the atmosphere as oxygen gas.

4. **Proteins in the electron transport chain pump protons across the thylakoid membrane into the interior of the thylakoid.**

   As electrons travel through the chain, plastoquinone (PQ) actively moves H^+ across the membrane.

5. **Protons flow back out of the thylakoids through ATP synthase.**

   ATP synthase transfers energy from the movement of H^+ to the chemical energy of ATP as it brings together ADP and P.

6. **Electrons move from the cytochromes to the reaction center of Photosystem I.**

   From the cytochrome chain, the electrons move to plastocyanin (PC) and then to photosystem I.

7. **Photosystem I absorbs light energy and transfers energy to the reaction center chlorophyll.**

   The electrons get another boost of energy and leave the reaction center chlorophyll.

8. **The enzyme *NADP reductase* transfers the electrons to the electron carrier, $NADPH^+$, reducing it to $NADPH + H^+$.**

Electrons move from photosystem I to ferredoxin (Fd) then to NADP reductase. Once the electrons move to NADPH, noncyclic photophosphorylation is complete.

WARNING

Oxygen (O_2) produced by photosynthesis doesn't come from carbon dioxide (CO_2). Oxygen is produced when water is split to provide electrons to the light reactions. Thus, the O_2 comes from the splitting of two H_2O molecules.

The steps of cyclic photophosphorylation

Photosystem I works with Photosystem II to form the Z scheme, but it can also work independently to produce ATP. When Photosystem I works on its own, it does cyclic photophosphorylation.

Here are the steps of cyclic photophosphorylation (follow along in Figure 5-7):

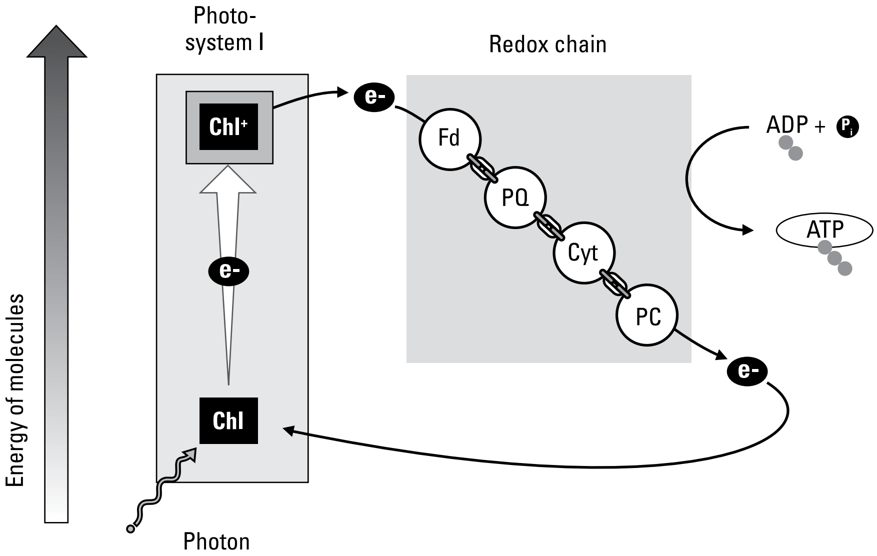


FIGURE 5-7: Cyclic photophosphorylation.

1. **Photosystem I absorbs light energy.**

The accessory pigments transfer light energy to the reaction center chlorophyll, exciting its electrons.

2. **Excited electrons leave the reaction center chlorophyll and move to the electron transport chain.**

   The electrons first move to ferredoxin (Fd) just like they would during noncyclic photophosphorylation. But when the electrons leave Fd, they move to PQ (not to NADP reductase). From PQ, they move to the cytochrome chain, and then to PC.

3. **Proteins in the electron transport chain pump protons across the thylakoid membrane into the interior of the thylakoid.**

   As electrons travel through the chain, plastoquinone (PQ) actively moves H^+ across the membrane.

4. **Protons flow back out of the thylakoids through ATP synthase.**

   ATP synthase transfers energy from the movement of H^+ to the chemical energy of ATP as it brings together ADP and P.

5. **Electrons return to their original reaction center.**

   The electrons return to chlorophyll, and the cycle can begin again.

REMEMBER

Cyclic photophosphorylation produces ATP but no $NADPH + H^+$.

Storing Matter and Energy in Sugar: The Light-Independent Reactions

For living things to grow, repair themselves, and reproduce, they need a source of building materials. The ultimate source of building materials for most life on earth traces back to one process: the light-independent reactions. The *light-independent reactions* transform inorganic carbon in the form of carbon dioxide (CO_2) into organic carbon in the form of carbohydrates. All living things build their cells using organic carbon that ultimately traces back to the light-independent reactions or similar processes.

REMEMBER

The light-independent reactions don't directly require light, but they do require the ATP and NADPH made during the light reactions. So, without light, the light-independent reactions will eventually shut down.

The steps of the light-independent reactions

REMEMBER

The light-independent reactions occur in the stroma of the chloroplast inside of plant cells.

Like most metabolic pathways, the light-independent reactions contain many small steps. These small steps ultimately lead to the production of carbohydrates from carbon dioxide. Scientists organize the light-independent reactions into four major events, shown in Figure 5-8:

1. **Carbon fixation: The enzyme rubisco attaches carbon dioxide molecules to a 5-carbon sugar called ribulose bisphosphate (RuBP).**

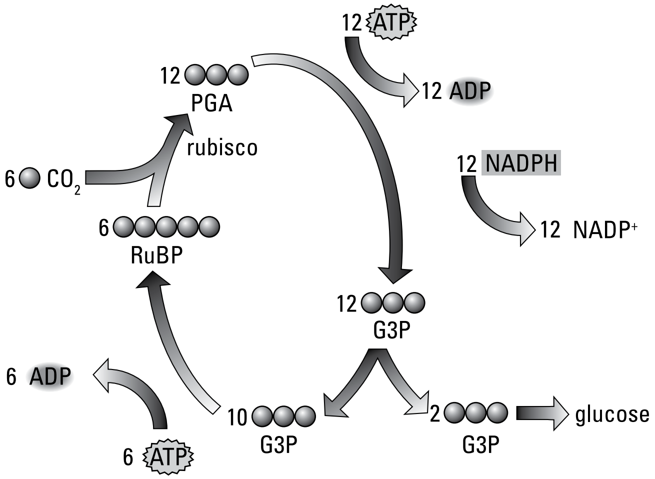


FIGURE 5-8: The light-independent reactions, also known as the Calvin cycle.

This critical first step captures the carbon dioxide from the environment and is called *carbon fixation*. The 6-carbon molecules that are formed by this step immediately split into two copies of a 3-carbon molecule. These 3-carbon molecules are called *3-phosphoglycerate* (PGA).

TIP

Rubisco is a much-needed nickname for the enzyme called ribulose-1,5-bisphosphate carboxylase/oxygenase.

2. **Reduction: Plants use energy from ATP and electrons from NADPH to create carbohydrates.**

   A phosphate group from ATP is transferred to PGA. Next, electrons from NADPH are transferred to the molecule, reducing it to the sugar *glyceraldedehyde-3-phosphate* (G3P).

3. **Biosynthesis: Some G3P is used to make glucose and other sugars.** Plants can combine 2 G3P molecules to make one molecule of glucose, then string glucose molecules together to form larger carbohydrates like starch and cellulose. Starch can be stored as a long term source of matter and energy.

4. **Regeneration: Some G3P and ATP are used to recreate RuBP.**

   Plants rearrange bonds between atoms in G3P to rebuild the 5-carbon sugar needed to restart the cycle.

Getting carbon dioxide to rubisco

Getting CO_2 to rubisco, the enzyme that captures carbon dioxide during photosynthesis, can be a tricky business for a plant. The way into the plant for CO_2 is through the stomata, but this is also the way out for H_2O. So, on hot sunny days, keeping your stomata open can be dangerous. So, what can a plant that lives in a hot sunny climate do? Close its stomata so that it doesn't dry out, but risk starvation because it can't make food?

And, it gets worse! If a plant does close its stomata to prevent water loss, the concentration of CO_2 in the leaf goes down as the plant uses it up. When CO_2 concentrations get low, rubisco starts to make mistakes. Instead of grabbing CO_2, it will capture O_2 instead, combining O_2 with RuBP in a process called *photorespiration.* Photorespiration produces a toxic molecule that the plant must neutralize, costing the plant energy in the process.

Two groups of plants, called *CAM plants* and *C_4 plants*, have worked out different solutions to the problem of getting carbon dioxide to Rubisco without losing too much water and without setting up conditions that favor photorespiration.

TIP

Both CAM and C_4 plants initially capture carbon via carbon fixation using the enzyme PEP carboxylase, which has a stronger affinity for CO_2 than does rubisco. So, in conditions that would normally cause rubisco to be inefficient, these plants can still capture the CO_2 they need.

Crassulacean acid metabolism (CAM) photosynthesis

Many plants that live in desert areas with high-light intensity and dry climate, including cacti and other succulents, protect their water supplies by opening their stomata at night when it's cooler. The CO_2 enters their cells, interacts with PEP carboxylase, and is attached to organic acids for temporary storage during the night. In the daytime, when light is available for photosynthesis, the acids release the CO_2 to Rubisco (while the stomata stay closed).

Figure 5-9 shows the steps of CAM photosynthesis:

1. **Stomata open at night to allow CO_2 to enter the plant and combine with phosphoenolpyruvate (PEP), producing 4-carbon acids.**

   The enzyme PEP carboxylase catalyzes the reaction between CO_2 and PEP. This reaction produces malic acid and oxaloacetic acid.

2. **The plant stores the 4-carbon acids in the vacuole of the cell.**

   The acids remain in the vacuole during the night.

3. **During the day, the 4-carbon acids break down, releasing CO_2 into the cell.**

   The plant captures the CO_2 and converts it into carbohydrates using the light-independent reactions.

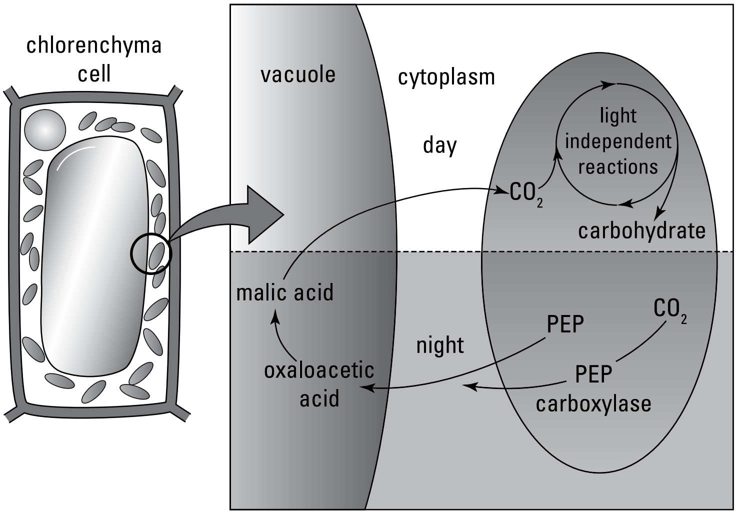

chlorenchyma cell
vacuole
cytoplasm
day
light independent reactions
CO_2
carbohydrate
malic acid
night
PEP
CO_2
oxaloacetic acid
PEP carboxylase

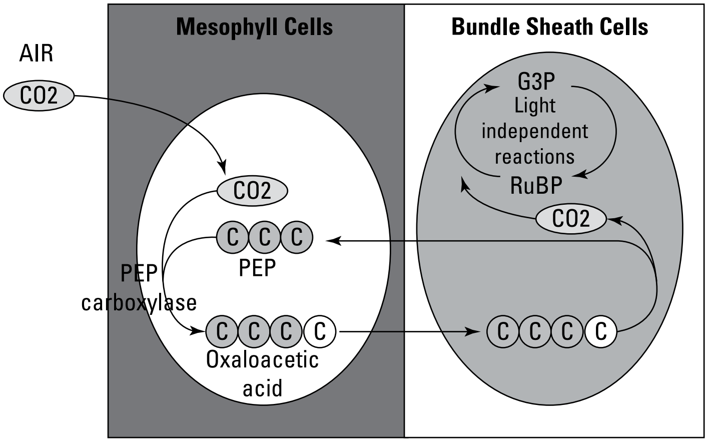
FIGURE 5-9: CAM photosynthesis.

C_4 photosynthesis

Many tropical plants use a system called C_4 photosynthesis to ensure high concentrations of CO_2 inside their cells even when stomata are closed on a hot day. These plants capture CO_2 in cells near the surface of the leaf where CO_2 is most available and then transport the CO_2 to cells in the interior of the leaf, concentrating it for use in the light-independent reactions.

Figure 5-10 shows the steps of C_4 photosynthesis:

FIGURE 5-10: CO_2 photosynthesis.



1. **Mesophyll cells in the exterior of the leaf attach C_4 to a PEP molecule, producing 4-carbon acids.**

   The enzyme PEP carboxylase catalyzes the reaction between CO_2 and PEP, producing oxaloacetic acid.

2. **The 4-carbon acid travels through plasmodesmata to bundle sheath cells near the interior of the leaf.**

   The bundle sheath cells produce all the enzymes necessary to do the light-independent reactions.

3. **The 4-carbon acid breaks down, releasing CO_2 into the bundle sheath cells.**

   C_4 plants create a high concentration of CO_2 in the bundle sheath cells, ensuring maximum success for rubisco.

TIP

Plants that fix carbon directly with rubisco, producing 3-carbon molecules are called C_3 plants because the first molecules they make after carbon fixation are 3-carbon molecules. Plants that fix carbon using PEP carboxylase to produce 4-carbon acids that are transported to bundle sheath cells are called C4 plants because the first molecules they make after carbon fixation are 4-carbon molecules. Plants that fix carbon using PEP carboxylase and then store acids in the vacuoles overnight are called CAM plants, which stands for Crassulacean acid metabolism, after the plant family, the Crassulaceae, in which this pathway was first discovered.

IN THIS CHAPTER

- **Realizing that plants do cellular respiration, too**
- **Understanding the purpose of cellular respiration**
- **Discovering the three stages of cellular respiration**
- **Digging into the details of glycolysis, the Krebs cycle, and oxidative phosphorylation**

Chapter 6

Cellular Respiration: Making Your Cake and Eating It, Too

Plants capture light, carbon dioxide, and water from the environment, using photosynthesis to combine the matter and energy into food molecules in the form of carbohydrates. Carbohydrates, such as starch, are a convenient way for plants to store matter and energy for future use. When plants want to access their stored matter and energy, they need to break down food molecules. To break down food, plants use the same process as people — cellular respiration! In this chapter, I present an overview of cellular respiration as well as some of the details of each stage of the process.

Digging into Cellular Respiration Fundamentals

Plants are famous for their ability to do photosynthesis (see Chapter 5), but very few people know they do cellular respiration, too. But if you stop to think about it for a minute, you'll probably see why it makes sense that plants use both processes:

- Photosynthesis captures energy from the sun and matter in the form of carbon dioxide (CO_2) and water (H_2O), storing the energy and matter in food molecules, such as the carbohydrate glucose ($C_6H_{12}O_6$).
- Cellular respiration breaks down food molecules, allowing cells to access the stored energy and matter so that they can use them to grow, repair themselves, and move — all the things plants need to do to sustain life. When food molecules are completely broken down by cellular respiration, the atoms from the food molecules are released as CO_2 and H_2O.

Cellular respiration and photosynthesis are like yin and yang to a plant — they complement each other. Another way of seeing this relationship is by looking at the summary reaction for cellular respiration and noticing how it's the opposite of the summary reaction for photosynthesis (see Chapter 5):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

TIP

You can think of photosynthesis as the way plants make lunch — storing away some food for when they need it. Cellular respiration is how plants eat that lunch — taking it out, breaking it down, and getting energy and building blocks from stored carbohydrates.

Cellular respiration is a little bit like burning a marshmallow. Food molecules are broken down into CO_2 and H_2O, and energy is released to the cell. When you burn a marshmallow, the food breaks down so quickly you can see and feel the energy as the light and heat from the flames. If cells broke down food molecules that quickly, they'd be cooked! So, cells have to control the burn, breaking down food molecules slowly in many small steps, releasing the energy gradually. Figure 6-1 compares the energy released from the direct burning of sugar, such as the sugar in a marshmallow, with the energy release from cellular respiration.

Cellular respiration is a complicated metabolic pathway, but it's easier to understand if you remember the basic principles of metabolism. Like all metabolic pathways, cellular respiration includes many chemical reactions, including redox reactions that move electrons from one molecule to another, and reactions that transfer energy.

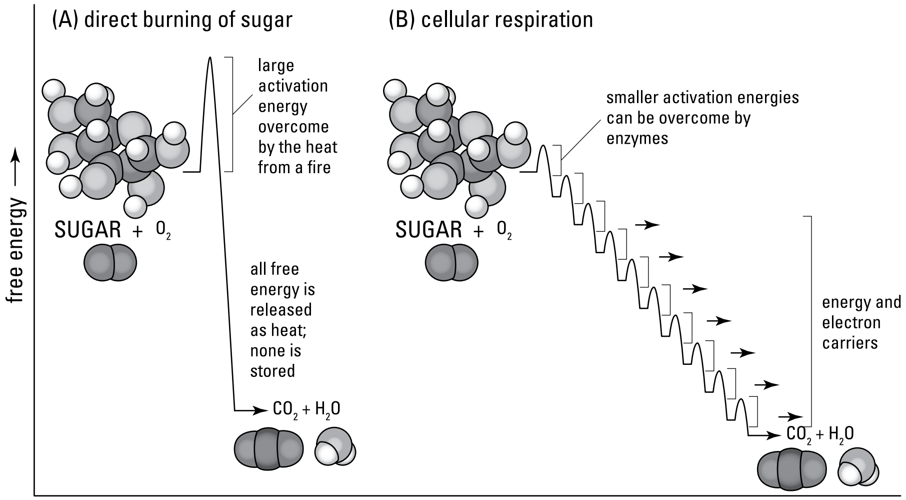

(A) direct burning of sugar
(B) cellular respiration
free energy
large activation energy overcome by the heat from a fire
all free energy is released as heat; none is stored
SUGAR + O_2
$CO_2 + H_2O$
smaller activation energies can be overcome by enzymes
energy and electron carriers
SUGAR + O_2
$CO_2 + H_2O$

FIGURE 6-1: A comparison of the direct burning of sugar with the breakdown of sugar via cellular respiration.

Here are some highlights of cellular respiration:

- During cellular respiration, electrons are removed from food molecules, transferred to the electron carrier NADH and then to oxygen (O_2).
- By the end of cellular respiration, the energy from food has been transferred to the energy carrier, ATP.
- Through many chemical reactions, cells completely rearrange food molecules into the waste products, carbon dioxide (CO_2), and water (H_2O).

REMEMBER

During cellular respiration, food molecules, such as glucose ($C_6H_{12}O_6$), are oxidized, and oxygen (O_2) is reduced (see Figure 6-2).

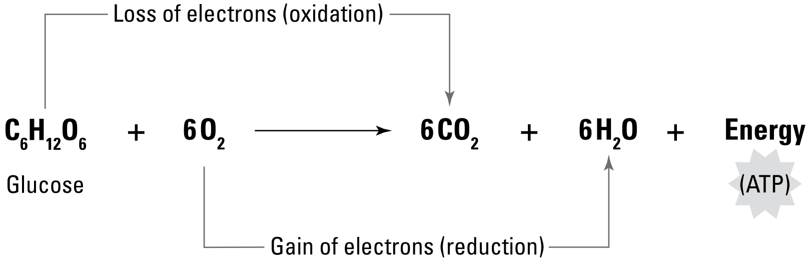

Loss of electrons (oxidation)
$C_6H_{12}O_6$ + $6O_2$ → $6CO_2$ + $6H_2O$ + Energy
Glucose
(ATP)
Gain of electrons (reduction)

FIGURE 6-2: Oxidation and reduction during cellular respiration.

Figure 6-2 shows the overall picture of oxidation and reduction during cellular respiration: Electrons from glucose eventually get handed over to oxygen. However, the actual metabolic pathway occurs in many small reactions that can be divided into three stages (see Figure 6-3):

- **Glycolysis:** Cellular respiration in a eukaryotic cell begins with glycolysis, which literally means the breakdown of glucose (*lyse* means to break). Enzymes in the cytoplasm of the plant cell rearrange the atoms in glucose, forming two molecules of pyruvate. Enzymes in glycolysis also transfer energy from glucose to ATP and electrons from glucose to electron carriers.
- **The Krebs or citric acid cycle:** The pyruvate molecules from glycolysis move into the mitochondria of the plant cell, where enzymes convert them into a molecule called acetyl-coA. Acetyl-coA enters a cyclic pathway that slowly breaks it down, releasing CO_2 as waste. During the Krebs cycle, enzymes transfer some energy to ATP and lots of electrons to electron carriers.

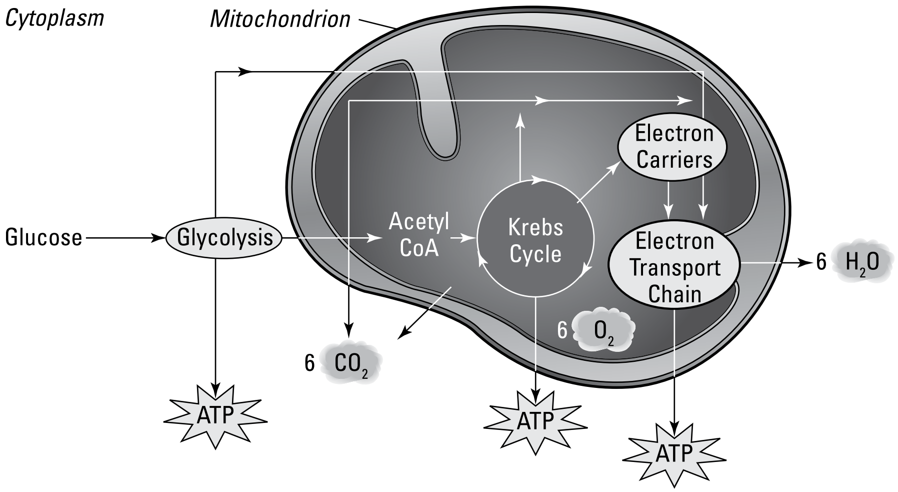


FIGURE 6-3: An overview of cellular respiration.

- **Oxidative phosphorylation:** The reduced electron carriers from glycolysis and the Krebs cycle travel to the inner membrane of the mitochondrion, which contains many electron transport chains. The carriers deliver electrons to the chains, providing the energy for the formation of ATP through chemiosmosis (see Chapter 5 for more on chemiosmosis).

Breaking Down Glucose in Glycolysis

REMEMBER

Glycolysis is a series of ten chemical reactions (shown in Figure 6-4) that oxidize glucose, transfer energy to ATP, and transfer electrons to the electron carrier NAD$^+$(which becomes NADH +H$^+$).

The most important events in glycolysis are as follows:

- **Enzymes break the bonds between the atoms in glucose, forming intermediates and then creating two molecules of pyruvate.** A glucose molecule has six carbon atoms, whereas a molecule of pyruvate has three carbon atoms, so in a way, glycolysis breaks glucose molecules in half.
- **Enzymes transfer energy from intermediates to ATP.** During the first part of glycolysis (steps 1 and 3), enzymes actually break down ATP, transferring a phosphate from ATP to the intermediates and increasing their stored energy. But then, in the second part of glycolysis, enzymes transfer even more energy from the intermediates to ATP (steps 7 and 10), leading to a net gain of ATP molecules. The first part of glycolysis, called the *energy investment phase*, uses two ATP but the second part of glycolysis, called the *energy payoff phase,* makes four ATP. Because 4-2=2, glycolysis produces a net gain of two ATP for the cell.
- **Enzymes oxidize glucose and reduce NAD$^+$.** Enzymes transfer electrons that were originally in glucose from an intermediate to NAD$^+$ (step 6), reducing the electron carrier to NADH + H$^+$.

REMEMBER

For every glucose molecule broken down in glycolysis, the reactions produce 2 ATP, 2NADH + 2H$^+$, and 2 molecules of pyruvate.

Glycolysis is universal

REMEMBER

Every cell on earth, including plants, animals, and bacteria, needs to break down food molecules to get energy and matter for growth. Even plants, which make their own food, need to break it down to access their stored matter and energy. So, all cells have the ability to do some form of glycolysis. (In fact some cells, such as bacteria and yeast, can get what they need to live from just glycolysis in a process called fermentation.) Variations in glycolysis exist among prokaryotes, but it seems that glycolysis is a necessary part of life on earth. And the fact that glycolysis is so widespread among many different types of cells suggests that it developed very early in the history of life on Earth.

Making ATP by substrate-level phosphorylation

When cells make ATP during glycolysis, they use a process called *substrate-level phosphorylation*.

REMEMBER

During *substrate-level phosphorylation*, cells make ATP by transferring a phosphate group from an intermediate in a metabolic pathway to ADP. An enzyme binds the intermediate and ADP in its active site and then catalyzes the transfer of the phosphate from the intermediate to ADP.

TIP

To remember how substrate level phosphorylation works, think about the words: *Substrate* refers to molecules that enzymes bind in their active sites, and *phosphorylation* means to add a phosphate to something — in this case, adding a phosphate to ADP to make ATP.

REMEMBER

Substrate-level phosphorylation occurs in Steps 7 and 10 of glycolysis.

More is better

Glycolysis only partially breaks down food molecules — the pyruvate from glycolysis still has lots of stored energy that a cell could use! To get that energy, cells move pyruvate into the mitochondria. As pyruvate enters the mitochondria, enzymes convert it to a molecule called acetyl-coA.

The conversion of pyruvate to acetyl-coA is called *pyruvate oxidation* (shown in Figure 6-5):

- **An enzyme oxidizes pyruvate, transferring electrons to NAD^+.** The reduction of NAD^+ forms $NADH + H^+$.
- **An enzyme removes carbon from pyruvate, releasing the carbon as CO_2.** Pyruvate has three carbon atoms, so this reaction produces a two-carbon molecule in addition to CO_2. The removal of a carbon atom from an intermediate is called *decarboxylation*.
- **An enzyme attaches a coenzyme, called coenzyme A, to the intermediate, forming acetyl-coA.** Coenzymes help enzymes function correctly. Coenzyme A attaches to the two-carbon molecule and helps catalyze the entry of acetyl-coA into the Krebs cycle. As acetyl-coA enters the Krebs cycle, an enzyme removes coenzyme A and releases it back into the mitochondrion.

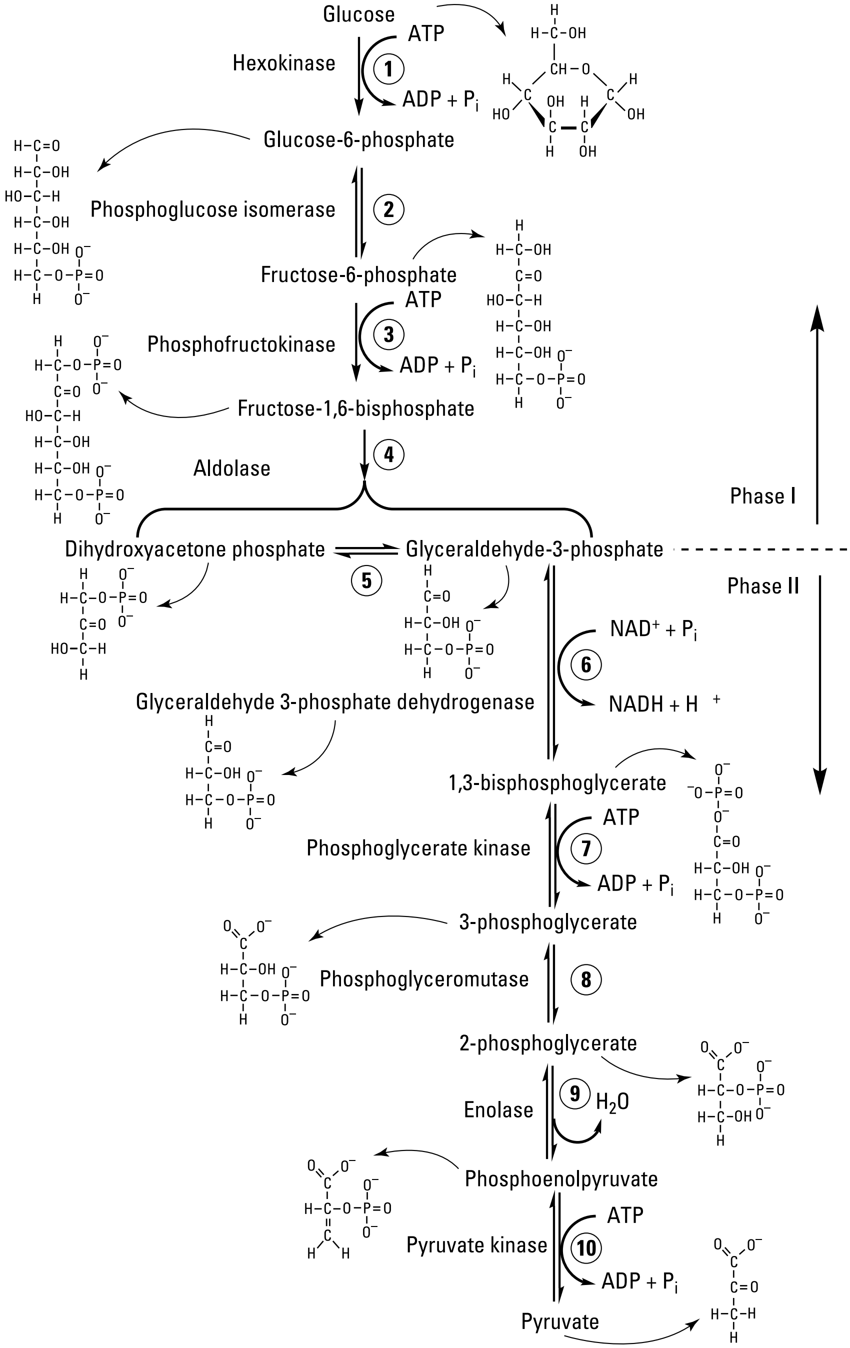

Glucose
ATP
Hexokinase
①
ADP + P_i
Glucose-6-phosphate
Phosphoglucose isomerase
②
Fructose-6-phosphate
ATP
Phosphofructokinase
③
ADP + P_i
Fructose-1,6-bisphosphate
④
Aldolase
Phase I
Dihydroxyacetone phosphate
⑤
Glyceraldehyde-3-phosphate
Phase II
$NAD^+ + P_i$
⑥
NADH + H^+
Glyceraldehyde 3-phosphate dehydrogenase
1,3-bisphosphoglycerate
ATP
Phosphoglycerate kinase
⑦
ADP + P_i
3-phosphoglycerate
Phosphoglyceromutase
⑧
2-phosphoglycerate
Enolase
⑨
H_2O
Phosphoenolpyruvate
ATP
Pyruvate kinase
⑩
ADP + P_i
Pyruvate

FIGURE 6-4: The steps of glycolysis.

TIP

The conversion of pyruvate to acetyl-coA has many names. Scientists call it *pyruvate oxidation*, the linking step (because it links glycolysis and Krebs), and the grooming step (because it grooms pyruvate for the Krebs cycle). I prefer the term *pyruvate oxidation* because I think that term is the clearest about what is actually happening.

Acetyl-coA still contains plenty of stored energy that a cell can use. Cells tap into that energy by sending acetyl-coA through the Krebs cycle. The Krebs cycle is basically a series of redox reactions that transfer energy and electrons from the acetyl-coA to energy and electron carriers.

Going Further with the Krebs Cycle

The Krebs cycle, or Citric Acid Cycle, picks up where glycolysis left off and involves many of the same types of reactions

REMEMBER

During the Krebs cycle, enzymes oxidize intermediates that came from food molecules, transferring electrons to electron carriers. Some energy is also transferred to ATP.

The most important events in the Krebs cycle are

- **Enzymes oxidize intermediates and reduce electron carriers.** Oxidation of intermediates is the real work of the Krebs cycle. Multiple redox reactions transfer electrons from intermediates in the cycle to the electron carriers NAD^+ and FAD. When FAD accepts electrons, it's reduced to $FADH_2$.
- **Enzymes break bonds and rearrange atoms in the intermediates, removing carbon and oxygen atoms and releasing them as CO_2.** For every molecule of pyruvate that leaves glycolysis and breaks down in the Krebs cycle, cells release three CO_2 molecules to the atmosphere. Because glycolysis produces two 3-carbon molecules from glucose, the Krebs cycle occurs twice for every molecule of glucose that enters cellular respiration. Thus, two rounds of pyruvate oxidation plus the Krebs cycle produce six molecules of CO_2 — releasing all six of the carbon atoms that were originally part of the glucose molecule. The last step of the Krebs cycle rearranges the atoms in the intermediate malate to recreate the intermediate, oxaloacetate, which is needed for the cycle to repeat again.
- **Enzymes transfer energy to ATP.** During one step of the Krebs cycle, energy is transferred to ATP by substrate-level phosphorylation. Because the Krebs cycle occurs twice for every glucose molecule that goes through cellular respiration, a total of 2 ATP per glucose are made during the Krebs cycle.

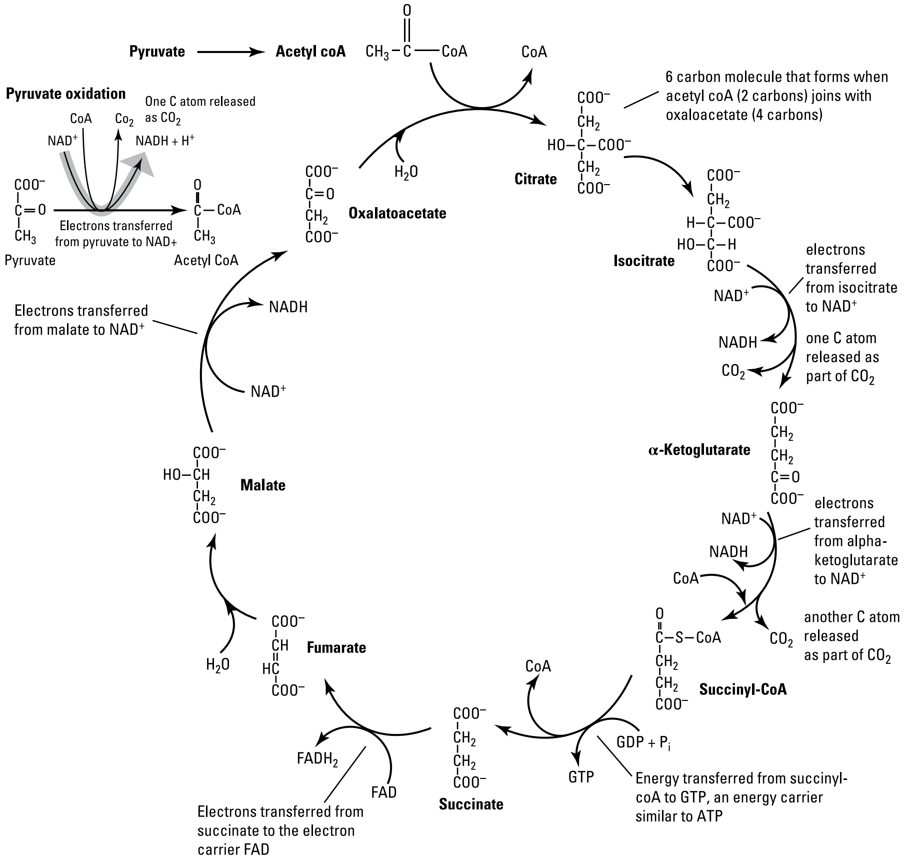

Pyruvate
Acetyl coA
CH3–C–CoA
O
CoA
Pyruvate oxidation
One C atom released as CO2
CoA
Co2
NAD+
NADH + H+
COO−
C=O
CH3
Pyruvate
Electrons transferred from pyruvate to NAD+
O
C–CoA
CH3
Acetyl CoA
6 carbon molecule that forms when acetyl coA (2 carbons) joins with oxaloacetate (4 carbons)
COO−
CH2
HO–C–COO−
CH2
COO−
Citrate
H2O
COO−
C=O
CH2
COO−
Oxalatoacetate
COO−
CH2
H–C–COO−
HO–C–H
COO−
Isocitrate
electrons transferred from isocitrate to NAD+
NAD+
NADH
CO2
one C atom released as part of CO2
Electrons transferred from malate to NAD+
NADH
NAD+
COO−
CH2
CH2
C=O
COO−
α-Ketoglutarate
COO−
HO–CH
CH2
COO−
Malate
NAD+
NADH
CoA
electrons transferred from alpha-ketoglutarate to NAD+
another C atom released as part of CO2
CO2
O
C–S–CoA
CH2
CH2
COO−
Succinyl-CoA
H2O
COO−
CH
HC
COO−
Fumarate
CoA
COO−
CH2
CH2
COO−
Succinate
GDP + Pi
GTP
Energy transferred from succinyl-coA to GTP, an energy carrier similar to ATP
FADH2
FAD
Electrons transferred from succinate to the electron carrier FAD

FIGURE 6-5: The Krebs cycle.

TIP

One of the most important functions of cellular respiration is to transfer energy from food molecules to a form that cells can use to do work. To get the energy out of food, cells oxidize food molecules. So, if you're a cell that is trying to get energy out of food, the more oxidation you do, the better, right? With that in mind, compare glycolysis and the Krebs cycle (refer to Figures 6-4 and 6-5). Glycolysis has one oxidation step, which you can recognize because $NADH + H^+$ is formed. Pyruvate oxidation and the Krebs cycle have a total of five oxidation steps, which you can recognize because $NADH + H^+$ and $FADH_2$ are formed. When you consider that the Krebs cycle happens twice per glucose molecule, that doubles the number of oxidation steps to 10! So, if oxidation of food molecules makes energy available to the cell, it's pretty clear which pathway gives more bang for each glucose molecule — cells that have the enzymes to do the Krebs cycle are much more efficient at extracting energy from their food than are cells that can do only glycolysis!

WARNING

Plants use pyruvate oxidation and the Krebs cycle to break down food molecules — and notice that both of these pathways produce CO_2! Most people think that plants take in CO_2 and release O_2, while humans breathe in O_2 and release CO_2 — which is actually true, but it's not the whole story! Plants do release O_2 and take in CO_2, but they also do what we do — they take in O_2 for cellular respiration and release CO_2 from the breakdown of food. It's just that in the light, plants are usually doing way more photosynthesis than respiration, so they're producing much more O_2 than they're using, and consuming way more CO_2 than they're releasing. So, if you measured the gases around a plant in the light, you'd get what everyone expects — overall, the plant would be taking in CO_2 and releasing O_2. However, if you put a plant in the dark, you'd be able to detect the rest of the story — a plant in the dark acts just like a human, taking in O_2 and releasing CO_2. Plants in the dark can't do photosynthesis, so you can actually see the evidence that they do cellular respiration.

Making Useful Energy: Chemiosmosis and Oxidative Phosphorylation

Plants use cellular respiration to break down food molecules so that the plants can access stored matter and energy. For every 6-carbon glucose molecule that's broken down through glycolysis and the Kreb's cycle, plants produce

- Six molecules of CO_2
- Four molecules of ATP
- Ten molecules of $NADH + H^+$, and
- Two molecules of $FADH_2$

By the end of glycolysis and the Krebs cycle, most of the energy from food molecules is stored in the NADH and $FADH_2$ molecules. To transfer that energy to ATP and complete cellular respiration, cells use a process called *oxidative phosphorylation*. Oxidative phosphorylation uses an electron transport chain in the inner membrane of the mitochondrion to transfer energy from reduced electron carriers to ATP by the process of chemiosmosis. (For more details on chemiosmosis, see Chapter 5.)

REMEMBER

The *chemiosmotic theory of oxidative phosphorylation* is a really big name for the explanation of how cells use an electron transport chain in the inner membrane of the mitochondrion to transfer energy from reduced electron carriers ($NADH + H^+$) to ATP.

Transferring electrons

REMEMBER

NADH and $FADH_2$ donate electrons to the electron transport chain during oxidative phosphorylation.

The electrons are pulled from complex to complex in the chain until they are accepted by O_2 at the end of the chain. When oxygen is reduced, it also accepts some H^+, forming H_2O.

REMEMBER

Molecular oxygen (O_2) is the final electron acceptor during oxidative phosphorylation in plants. Oxygen is very electronegative, so it makes a great electron acceptor. When the oxygen accepts electrons, it's reduced to water (H_2O).

NADH and $FADH_2$ are oxidized as they donate electrons to the beginning of the electron transport chain, converting them back to NAD^+ and FAD. The oxidized carriers can now go back to glycolysis and Krebs and accept more electrons.

Transferring energy

As electrons move through the electron transport chain during oxidative phosphorylation, energy is transferred to ATP via chemiosmosis.

The essential steps of chemiosmosis during oxidative phosphorylation are the same as those that occur during chemiosmosis of photosynthesis:

1. **Energy and electrons are donated to an electron transport chain.**

   During cellular respiration, the energy and electrons originally came from food and are donated to the chain by $NADH + H^+$ and $FADH_2$.

2. **As the electrons move through the chain, the protein complexes access some energy to pump protons (H^+) across a membrane.**

   The concentrated hydrogen ions represent a source of potential energy called proton motive force.

   REMEMBER

   During oxidative phosphorylation, the protons are pumped across the inner membrane of the mitochondrion, into the intermembrane space between the two mitochondrial membranes.

3. **The protein ATP synthase allows hydrogen ions to move back across the membrane.**

   As the hydrogen ions move, they cause part of ATP synthase to rotate, which increases energy in the ATP synthase. The enzyme uses this energy to join ADP and phosphate groups, making ATP. ATP finally stores the energy from food!

Plants can now use the ATP as a source of energy for growth, repair, movement of molecules, and other types of cellular work.

TECHNICAL STUFF

ATP synthase is embedded in the inner mitochondrial membrane right along with the electron transport chain (see Figure 6-6). On one side of the membrane is the intermembrane space; on the other side is the matrix of the mitochondrion. During oxidative phosphorylation, hydrogen ions (H^+), which are also called protons, enter a small channel in ATP synthase from the intermembrane space side of the membrane. The protons bind to the ATP synthase and then exit the protein on the matrix side. As they bind to the ATP synthase, the head of the protein rotates. The base of the protein has binding sites for ADP and inorganic phosphate (P_i). The passage of every three protons through the ATP synthase provides enough energy for the synthesis of one ATP molecule from ADP and P_i.

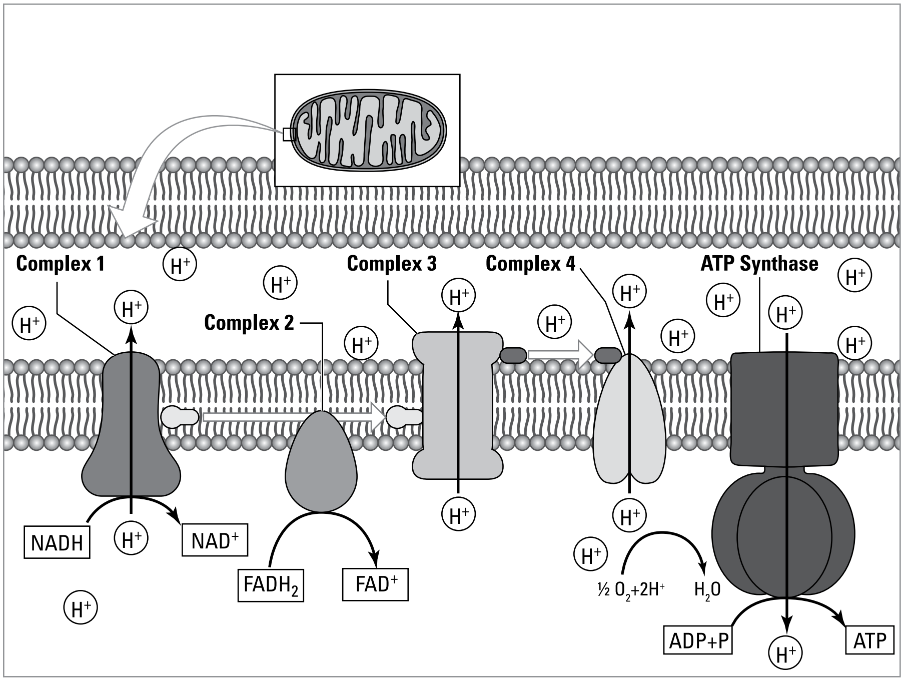


FIGURE 6-6: The electron transport chain in the inner membrane of the mitochondrion.

REMEMBER

Chemiosmosis occurs as part of cellular respiration and also photosynthesis (see Chapter 5).

IN THIS CHAPTER

- **Transporting molecules across plasma membranes**
- **Making water flow according to the cohesion-tension theory**
- **Moving sugars with the pressure-flow hypothesis**

Chapter 7

Moving Materials through Plants

Plants make sugars in their leaves and then must move those sugars throughout the plant in order to provide sugar to all the plant cells. Likewise, water and minerals are taken up by plant roots and then must be transported to all the plant cells. Once the circulating materials arrive at plant cells, they must be moved into the cells. This chapter explains how plants move sugar and water throughout their bodies and how individual plant cells get what they need to survive.

Shipping and Receiving Materials throughout the Plant

You can think of a plant as a factory, with different areas that specialize in the manufacturing of components that everybody needs. The leaves specialize in making food, while the roots specialize in getting water and minerals. However, every cell in the plant needs both of these components in order to survive. So, plants need efficient shipping mechanisms to circulate both sugar and water throughout their bodies. Figure 7-1 gives an overview of how these materials circulate through plants so that every cell can get what it needs.

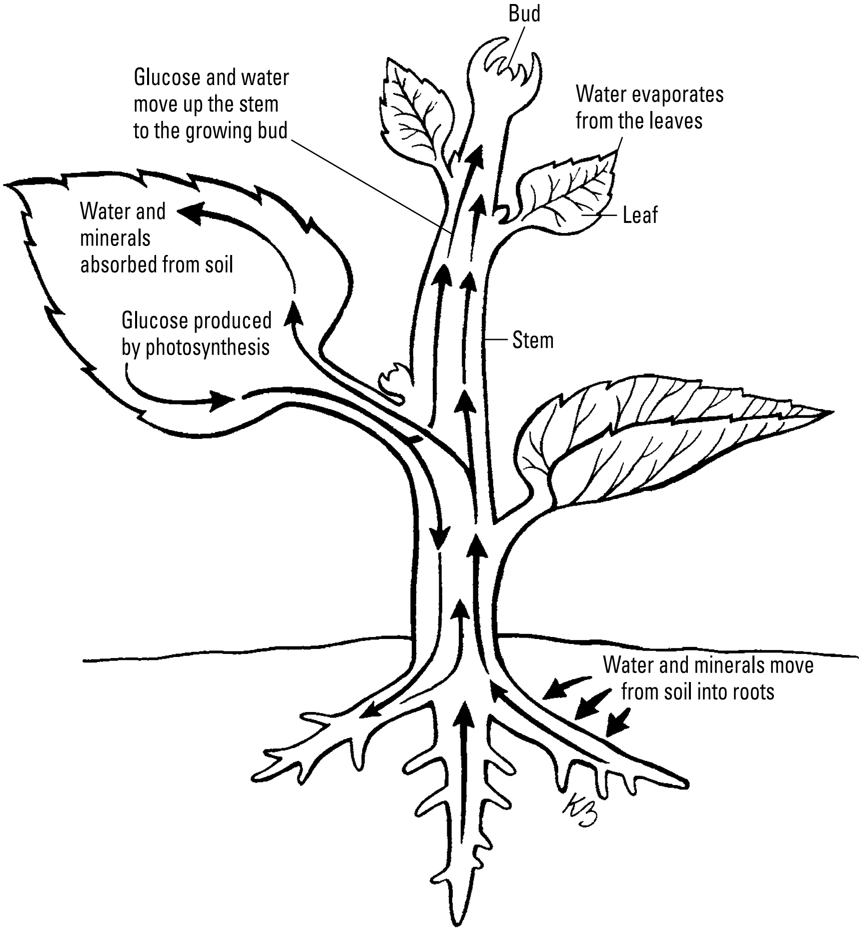

Bud
Glucose and water move up the stem to the growing bud
Water evaporates from the leaves
Leaf
Water and minerals absorbed from soil
Glucose produced by photosynthesis
Stem
Water and minerals move from soil into roots
KB

FIGURE 7-1: Overview of the movement of molecules through plants.

Moving across Membranes

The plasma membrane controls what can enter and exit each plant cell. (See Chapter 2 for the basic structure and function of plasma membranes.) Whether or not a molecule will cross a membrane, and which way it will go, depends upon three things:

- **The chemical structure of the molecule, particularly its size and whether it's hydrophobic or hydrophilic.** Small, hydrophobic molecules can cross the lipids in the plasma membrane all by themselves. As molecules get larger, or if they're hydrophilic, they can cross the membrane only if a transport protein in the membrane helps them across.

- **The concentration of the molecule on either side of the membrane.** If molecules are allowed to move freely, they will move from areas where they're more concentrated to areas where they are less concentrated — in other words, they'll move until they're evenly spread out, or in *equilibrium,* over an area. This type of movement, called *diffusion,* is explained in more detail in the next section.
- **Whether the membrane contains a transport protein for the molecule.** Although some small hydrophobic molecules can cross membranes by themselves, most molecules need the help of a transport protein. If a plant plasma membrane doesn't have a protein to transport a particular molecule, it won't be able to cross in or out of the plant cell.

Diffusion

Diffusion is the movement of molecules from an area of higher concentration to an area of lower concentration. Diffusion is a passive process and requires no energy to be input from the cell.

Figure 7-2 shows how diffusion across a membrane works:

1. **A chemical starts out more concentrated on one side of a membrane, but its molecules can cross the membrane freely.**
2. **The molecules bounce around due to kinetic energy and gradually become equal in concentration on both sides of the membrane.**
3. **If you measure the overall movement of the chemical, you can see that its molecules moved from the side of the membrane where they were more concentrated to the side where they were less concentrated.**

When molecules move from where they are more concentrated to where they are less concentrated, scientists say that molecules are moving along their *concentration gradient.*

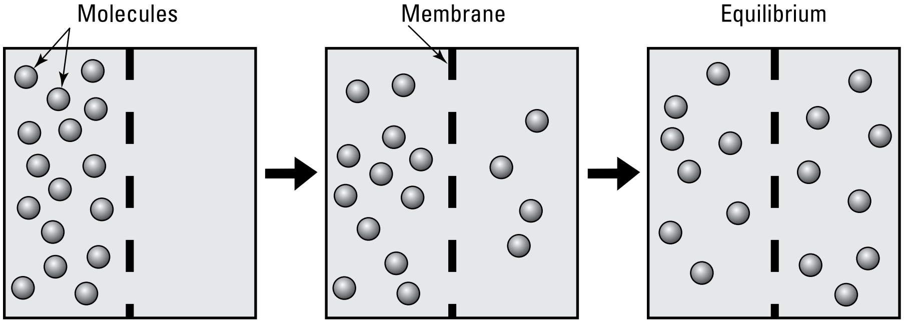


FIGURE 7-2: Diffusion of molecules.

Figure 7-3 shows two basic types of diffusion that occur across plant cell membranes:

- *Simple diffusion* occurs when molecules diffuse across a membrane all by themselves.
- *Facilitated diffusion* occurs when molecules diffuse across a membrane with the help of a membrane protein. (See Chapter 2 for details on how proteins help molecules across membranes.)

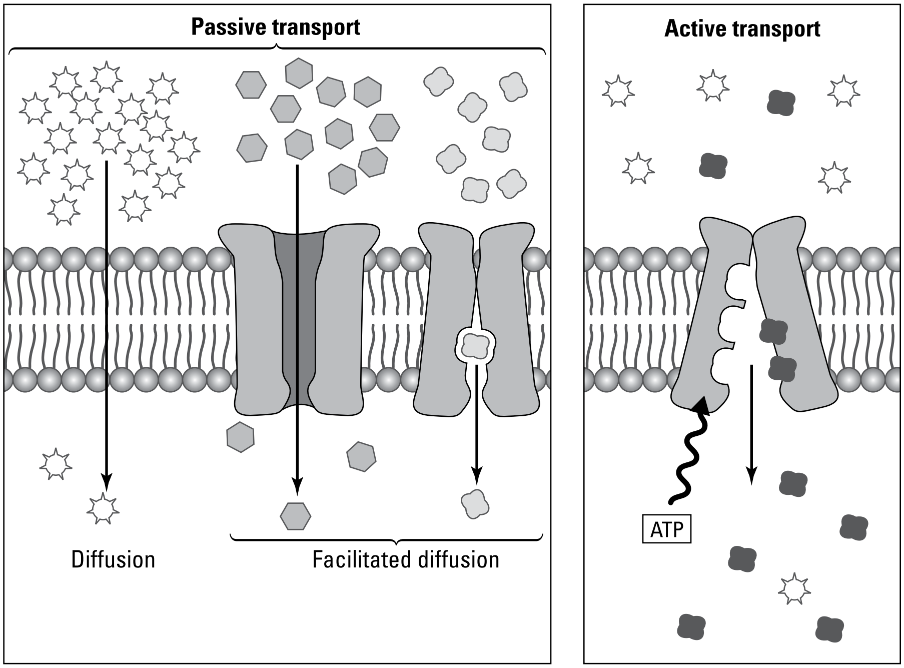


FIGURE 7-3: Transport across membranes.

Active transport

Plant cells often need to move molecules from areas where the molecules are less concentrated to areas where they're more concentrated, a process called *active transport*. In other words, plant cells need to move molecules against their concentration gradient.

Active transport requires the input of energy from the cell. Active transport is like rolling molecules up the hill of their concentration, going from where they're less piled up to where they're more piled up. If a cell is going to move something up hill, it's going to have to put some energy into the process.

Figure 7-3, earlier in this chapter, shows how a carrier protein could move a molecule against its concentration gradient by getting energy from ATP molecules during the transport process. Scientists call these proteins *active transport proteins*, or *pumps.* As an example, a plant cell that stores energy for the plant may have lots of glucose inside the cell, but it may still need to bring in more. This cell could use active transport to continue bringing glucose molecules in against their concentration gradient.

Osmosis

Water moves across membranes by diffusion. The diffusion of water across membranes is called *osmosis*. During osmosis, water moves from an area where water is more concentrated to an area where water is less concentrated.

Thinking about osmosis in terms of water concentration can be a little hard to wrap your head around: Water is more concentrated when fewer solutes are dissolved in the water. In other words, water is most concentrated where water is most pure. So water moves from where water is most pure to areas where water is less pure.

If thinking of osmosis in terms of water concentration is confusing, think of osmosis in terms of solute concentration instead. Water will diffuse into an area of greater solutes. The concentration of solutes on either side of a membrane can be described by three terms that are used to describe the relative concentrations of solutes in different solutions:

- *Hypertonic* solutions have greater concentrations of solutes (*hyper-* means more).
- *Hypotonic* solutions have lesser concentrations of solutes (*hypo-* means under).
- *Isotonic* solutions have the same concentration of solutes (*iso-* means same).

If you have two different concentrations of a chemical on either side of a membrane, water will move by osmosis toward the hypertonic solution. As an example, refer back to Figure 7-2. Solutes move by diffusion from left to right until they're evenly distributed across the membrane. But, in that same scenario, what would the water around those solutes be doing?

1. **Initially, the solution on the left side of the membrane is hypertonic to the solution on the right side of the membrane because more molecules are dissolved in the solution on the left side.**

2. **Water molecules move by osmosis toward the hypertonic solution — in other words from the right side to the left side of the membrane.**
3. **If the membrane is permeable to both the solute and the water, they will diffuse in opposite directions until both are randomly distributed across the membrane.**

TIP

One way to remember which way water will move by osmosis is to remember the phrase "salt sucks." Salt is a solute, and water moves into solutions with more solutes (hypertonic). So, a solution with more "salt" (solutes) will "suck" water toward it.

WARNING

Living cells don't allow everything to pass freely across their membranes. Certain solutes require a protein transporter to help them get across. So, in a living cell, water may move by osmosis until its concentration is the same across a membrane, while a particular solute may remain unevenly distributed. To determine whether the solute will move, you need to know whether it needs a transport protein and, if so, whether the cell in question has that transport protein.

Under pressure

Water movement in plant cells is complicated by the fact that plant cells may also be under pressure. As plant cells fill up their central vacuoles with water, their plasma membranes push against the walls around the cells. The pressure on plant cells that results from the uptake of water is called *turgor pressure.*

As water flows into a plant cell and the cell becomes increasingly firm, or *turgid*, the increase in turgor pressure may slow the movement of water even if the water concentration hasn't yet reached equilibrium.

Whether or not water moves in or out of plant cells depends upon both turgor pressure and solute concentration. Botanists combine both of these factors to determine *water potential* of a cell. Water potential is represented by the Ψ symbol and is measured in megapascals (mPa), which is a unit of pressure (one atmosphere, which is the pressure that the atmosphere puts on the earth at sea level, equals 0.1 mPa).

You can think of water potential as the tendency of water to leave one place in favor of another. To figure out the water potential of a cell or solution within a plant, you add together the effects of solute concentration and turgor pressure:

- **Botanists express the effect of solute concentration as *solute potential* (ψ_S), which is sometimes called *osmotic potential*.** The solute potential of pure water equals zero. As solutes are added to water, the solute potential becomes more negative, so plant cells always have negative solute potential.
- **Botanists express the effect of turgor pressure as *pressure potential* (ψ_P).** Normal atmospheric pressure at sea level has a pressure potential equal to 0. As turgor pressure in a cell increases above normal atmospheric pressure, pressure potential becomes more positive.

To determine overall water potential, solute potential and pressure potential are added together using the equation:

$$\Psi = \Psi_{S+}\Psi_P$$

REMEMBER

Water always moves from an area of higher water potential to an area of lower water potential.

Table 7-1 shows how the water potential equation compares to the concepts of how water moves in response to solute concentration and pressure.

TABLE 7-1 Relating Concepts of Water Movement to the Water Potential Equation

Concept	Equation
Water moves by osmosis to an area of greater solute concentrations.	As solute concentration increases, the value of Ψ_S decreases, lowering the overall water potential. So, the more solute in a solution, the lower its water potential. If two solutions are in contact, the one with more solutes has a lower water potential, so water will move by osmosis to the hypertonic solution.
Increasing turgor pressure will slow the movement of water into a plant cell.	As turgor pressure increases, the value of Ψ_S increases, raising the overall water potential. So, as turgor pressure increases, the overall water potential increases, which lessens the chances that water will move into the cell.

Losing it

Water can move into plant cells, and it can move out of plant cells, too. If you put crisp celery or carrot sticks into a salty cup of water, they'll pretty quickly get limp and rubbery as they lose their turgor pressure. Because of the dissolved salt, the salty water has a lower water potential than the plant cells. Water flows out of the plant cells, and the cells no longer push up against their cell walls. Turgor pressure is lost, and the vegetables become limp.

If you looked at the cells in the vegetables under a microscope, you'd see something like the *plasmolyzed* cell drawn in Figure 7-4. When water leaves a walled cell through osmosis, the cytoplasm collapses, and the plasma membrane pulls away from the cell wall. This collapse of the cell is called *plasmolysis*.

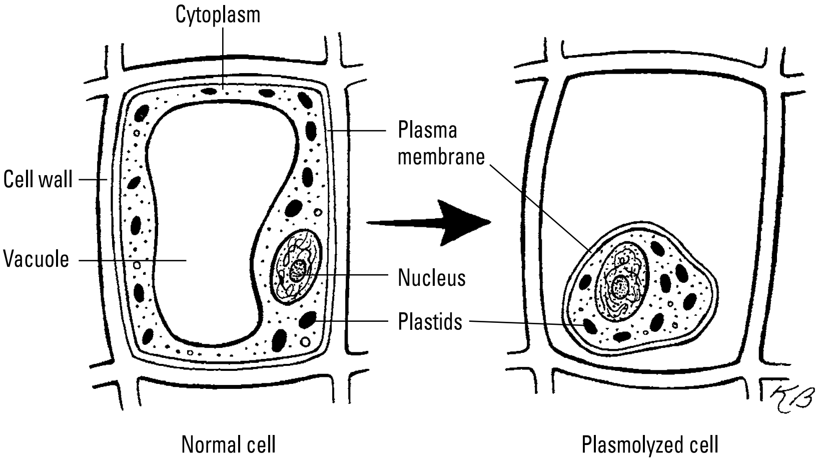


FIGURE 7-4: Plasmolysis.

Going with the Flow: Water Transport

Plants transport water through their *xylem,* which is mostly made up of dead cells whose strong secondary cell walls form tubes throughout the plant. (See Chapter 2 for details on the cells that make up this tissue.) So, the xylem itself isn't actively moving water through the plant; instead, it's like the pipes in the plumbing of your home — hollowed out tubes through which water can move.

Water moves through plants by a combination of two factors:

- The adhesive and cohesive properties of water
- The pull of water evaporation from the leaves *(transpiration)*

REMEMBER

Botanists call the explanation for how water moves through plants the *cohesion-tension theory*.

Clinging for support: The cohesion of water

Water molecules stick together due to the hydrogen bonds that form between them. Although each individual hydrogen bond is just a weak electrical attraction, when you combine lots of hydrogen bonds together, the attraction becomes very powerful — so powerful, for example, that a person can put on a pair of water skis and slide across the surface of a lake. If water molecules didn't stick together to create a resistance called *surface tension*, the skier would fall right in!

REMEMBER

Cohesion describes the attraction between water molecules and *adhesion* describes the attraction between water and other substances.

One way to visualize the importance of cohesion and adhesion in water movement through xylem is to look at how water moves through narrow tubes called *capillary tubes. Capillary action* occurs when a narrow tube pulls a liquid upward against the force of gravity. Figure 7-5 illustrates capillary action in tubes of different diameters:

- **When narrow tubes are placed in water, water will automatically creep upward in the tube due to adhesive forces between water molecules and the molecules that make up the tube.** The water molecules are attracted to the molecules in the solid material, such as glass, that makes up the tube. The adhesive forces between the water molecules and the sides of the tube cause the water molecules to cling to the solid surface. The water molecules along the edges cling to the solid tube (adhesion) and also to the other water molecules (cohesion), pulling the water upward in the tube.
- **The narrower the tube, the higher the water will move.** Gravity also acts on the water molecules, pulling them downward. So, the height of the column of water depends upon the balance of forces between the attraction to move upward in the tube and the downward pull of gravity. In a narrow tube, more contact occurs between the water molecules and the molecules of the tube itself, so relatively more force is causing the water to move upward than there would be in a wider tube.

In a plant, capillary action occurs when water moves through the narrow tubes of xylem:

- Cohesive forces between the water molecules themselves act as the glue that holds the column of water together.
- Adhesive forces between the water molecules and the cellulose microfibrils that make up the cell walls of the xylem draw the water column up the xylem. The water column will rise until the adhesive forces are balanced by the downward pull of gravity. Xylem tubes are very narrow, so lots of contact occurs between the water and the cell walls, helping the upward movement of the water column.

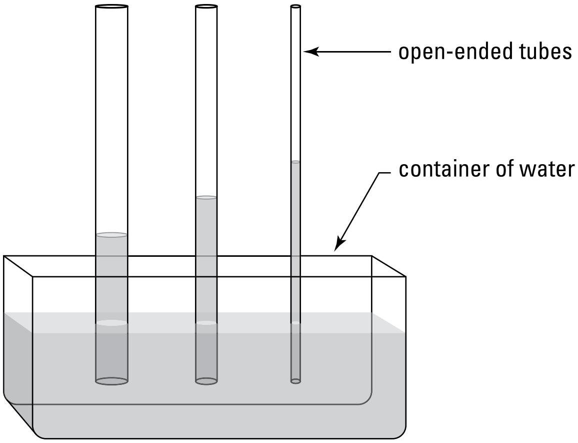


FIGURE 7-5: Capillary action.

The pull from above: Transpiration

Capillary action (see preceding section) explains how a column of water would rise upward and then remain hanging in the narrow tubes of xylem in a plant, but it's not enough to explain what makes water keep flowing upward from the roots to the leaves. Water moves upward through the xylem because water that evaporates from the leaves is replaced by water from the continuous column in the xylem. The evaporation of water from the leaves is called *transpiration.*

Water moves through a plant and out into the atmosphere because of the gradient of water potential created by transpiration. (See the earlier section "Under pressure" for an explanation of water potential.) Figure 7-6 shows the flow of water through a plant and out into the atmosphere:

1. **The atmosphere has a very negative water potential, more negative than the water potential of the air in the leaf.**

   So, water moves from the leaf air into the atmosphere.
2. **The leaf air has a more negative water potential than the leaf cells, so water moves from the leaf cells into the leaf air.**
3. **The leaf cells have a more negative water potential than the column of water in the xylem, so water moves from the xylem into the leaf cells.**
4. **The column of water has a more negative water potential than the root cells, so water moves from the root cells into the xylem.**
5. **The root cells have a more negative water potential than the soil, so water moves from the soil into the root cells.**

REMEMBER

The rate of water movement through the plant depends upon the rate of transpiration. Anything that increases the rate of transpiration will increase the rate of water movement through the plant.

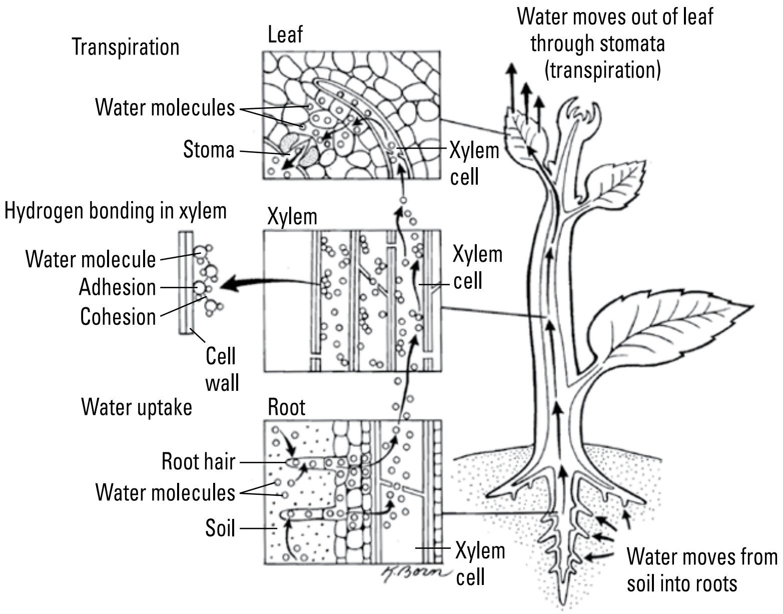

Transpiration
Leaf
Water moves out of leaf through stomata (transpiration)
Water molecules
Stoma
Xylem cell
Hydrogen bonding in xylem
Xylem
Water molecule
Adhesion
Cohesion
Cell wall
Xylem cell
Water uptake
Root
Root hair
Water molecules
Soil
Xylem cell
Water moves from soil into roots

FIGURE 7-6: The movement of water through a plant.

Several environmental factors can increase the rate of transpiration:

- When the air around a plant is dry, its water potential is lower, increasing the rate of transpiration.
- If the wind is blowing, water vapor surrounding the leaf will be swept away, which also lowers the water potential of the air around the leaf, increasing transpiration.
- Increases in temperature increase the vapor pressure of water, which increases the rate of transpiration.
- Anything that causes stomata to open has the potential to increase transpiration.

Different signals cause stomata to open:

1. **The guard cells that surround the stomata have receptors for environmental signals, such as light and carbon dioxide (CO_2).**

2. **When the guard cells detect that light is available or that the concentration of CO_2 is low, they actively transport hydrogen ions (H^+) out of the cell, causing the guard cells to become negatively charged.**
3. **The negative charge on the guard cells encourages positively charged potassium ions (K^+) to enter the cell, decreasing the water potential of the guard cells (because solute potential becomes lower).**
4. **When the water potential of the guard cells is lowered, water moves by osmosis into the cells, making them more turgid.**
5. **When guard cells become turgid, they pull away from the stomata, allowing more transpiration to occur.**

REMEMBER

Transpiration essentially pulls the water columns up through the plant. The pulling force of transpiration is the opposite of the pushing force of pressure, so botanists refer to it as *negative pressure* or *tension.*

TIP

Water moving through a plant works in a process very similar to the one that happens when you drink water through a straw. You provide suction (negative pressure) with your mouth, just like transpiration lowers the water potential outside the leaf. As you suck on the straw, water clings to the edges of the straw through adhesion and sticks together in a column because of cohesion. This is exactly what happens inside the tubes of xylem in a plant!

Fixing a break in the lines: Cavitation

In order for water columns to move up plants, the water molecules need to stick to each other. If anything happens to introduce an air bubble into the column of water, the column of water below the air bubble will drop, and water movement in that column will stop.

REMEMBER

The sudden formation of gas bubbles in a liquid is called *cavitation*. Several factors can cause cavitation in the xylem of plants:

- On a hot, dry day, the tension on water columns due to rapid transpiration may exceed the cohesive forces that hold the water column together. The water molecules get pulled apart and separated by a gas bubble.
- Dissolved gases in the water column may come out of solution, creating a gas bubble.
- Freezing and thawing cause changes in the arrangements of the water molecules that can lead to the introduction of gas bubbles.

Because plants rely upon cohesion of water molecules to move water through the plant, cavitation is potentially a serious problem. But, as is typical of living things, where there's a problem, there's a solution:

- **Plants that experience high levels of cavitation may rely upon tracheids rather than vessels for water transport.** Vessel elements are wide open tubes, whereas tracheids have more enclosed ends. Also, tracheids have pits that allow for lateral water transport as well as vertical water transport. So, if an air bubble occurs in a vessel element, the whole water column is blocked. But if an air bubble occurs in a tracheid, the bubble may be contained to a single tracheid cell. Water may be able to find a new path around that blocked cell by traveling through the pits of the surrounding tracheids. Arctic plants, which experience lots of freezing and thawing that can cause cavitation, rely upon tracheids instead of vessels.
- **Woody plants form new xylem every year.** One solution to xylem that doesn't work anymore because of air bubbles is to just ignore it and make new xylem.
- **At night, plants use *root pressure* to force water upward and repair broken water columns.** At night, root cells release ions into the xylem, lowering its solute potential and, thus, its water potential. As a result, water flows into the xylem. If the incoming water pushes a broken water column up through an air gap until it touches the rest of the column, then the water column is restored. Root pressure is most effective in restoring water in shorter plants as the maximum height a water column can be forced upward by this method is about 60 feet.

Reaching out with roots

Water enters plants through the roots. As rain enters the soil, the water molecules are attracted to soil particles. The water coats the soil particles, forming multiple layers of water shells. The water shells closest to the soil particle have the most negative water potential, so the innermost water shells are held tightly to the soil particle. In order for a plant to get water from the soil, root cells must come into contact with the water shells around the soil particle. Because water always moves to the lower water potential, plants can attract water only from the shells that have a higher water potential than the root cells themselves. So, roots typically can't take all the water from the soil.

In order to get enough water to survive, plants increase contact between root cells and soil particles (see Chapter 3 for details on root structure, root hairs, and mycorrhizal fungi):

- **Branch roots** spread more root mass through the soil, increasing the contact between roots and soil particles.
- **Root hairs are single cells that** extend out into the soil, increasing the surface area of contact between roots and soil particles. Water enters the

roots through these root hairs, which are found on branch roots, fibrous roots, and taproots.

- **Taproots** extend down into the soil in order to contact water that may be found deep in the soil.
- **Mycorrhizal fungi** that associate with roots also extend the reach of roots throughout the soil.

As roots take up water, they also take up *mineral nutrients* for plant growth. Plants get 13 minerals from the soil (see Chapter 5 for more details). As rocks in the soil dissolve, they release ions into the soil. These ions are dissolved in the water shells around the soil particles and get taken into plants as they take up water. It's not always easy for plants to get these minerals because positively charged ions, called *cations*, are attracted and cling to the negatively charged surfaces of clay particles in the soil. But plants can loosen these minerals by doing *cation exchange* — plants release cations, such as hydrogen ions, (H^+), which are also attracted to the clay and can bump off some of the other cations, making them available for absorption by the plant. Because ions can only enter plant cells through membrane transport proteins, cells in the plant roots screen the ions and only allow valuable ions to enter the plant. And the waxy *casparian strip* (see Chapter 3) helps make sure that all water flowing through the root must actually enter root cells at some point.

Sticky Business: Sugar Transport

Plants transport sugars through their phloem. Like the xylem, phloem is made up of tubes of cells connected end to end. However, unlike the cells of the xylem, the sieve tubes and companion cells of phloem aren't dead. The cells of phloem transport ions and sugars across their membranes in order to start the process of sugar transport.

REMEMBER

Plants move sugar through their phloem by actively transporting solutes in order to manipulate the flow of water. Turgor pressure in the phloem is increased in areas of the plant where sugars are available *(sources)* and decreased in areas of the plant where sugars are needed *(sinks).*

Sources and sinks

Green parts of plants, such as leaves, make sugars through photosynthesis, so they're the ultimate source of sugars for plants. In addition, sugars may be stored in roots or stems and then accessed later when needed. When sugars are taken from the roots — for example, in the spring — then roots become a *source* for sugars for the plant.

Every part of the plant needs sugar, especially rapidly growing areas like stem tips and developing fruits. These high demand areas are *sinks* for sugar. During the growing season, plants may use roots or underground stems for storage, making them another sink for sugar. And in the spring, when new buds break open and begin to grow, they become a significant sink for sugars.

The pressure-flow hypothesis

Botanists studying the movement of sugars through phloem have summed up their observations in an explanation called the *pressure-flow hypothesis*. According to this hypothesis, shown in Figure 7-7, sugars are moved through phloem by the movement of water in response to changes in water potential.

Events at the source are

1. **Phloem cells at the source actively transport sugars into the sieve tubes.**
2. **As sugars enter the sieve tube, the solute potential becomes more negative, which lowers the water potential.**
3. **Water enters the sieve tube from nearby xylem by osmosis because of the lowered water potential.**
4. **The influx of water increases pressure in the sieve tube and pushes material through the tube.**

   Because sieve tube cells have porous cell walls at their ends, much of the fluid part of each cell is moved to the next cell in a process called *bulk flow.*

Events at the sink are

1. **Plant cells at the sink remove sugars from the sieve tubes by active transport and either use the sugars immediately or convert them into starch for storage.**
2. **As sugars leave the sieve tube, the water potential inside the sieve tube becomes less negative.**
3. **Water leaves the sieve tubes by osmosis and moves into the surrounding tissues, which have a lower potential.**
4. **As water leaves the sieve tubes, the pressure inside the tubes decreases.**

REMEMBER

The pressure gradient between sources and sinks causes sugars to move through the phloem from sources to sinks.

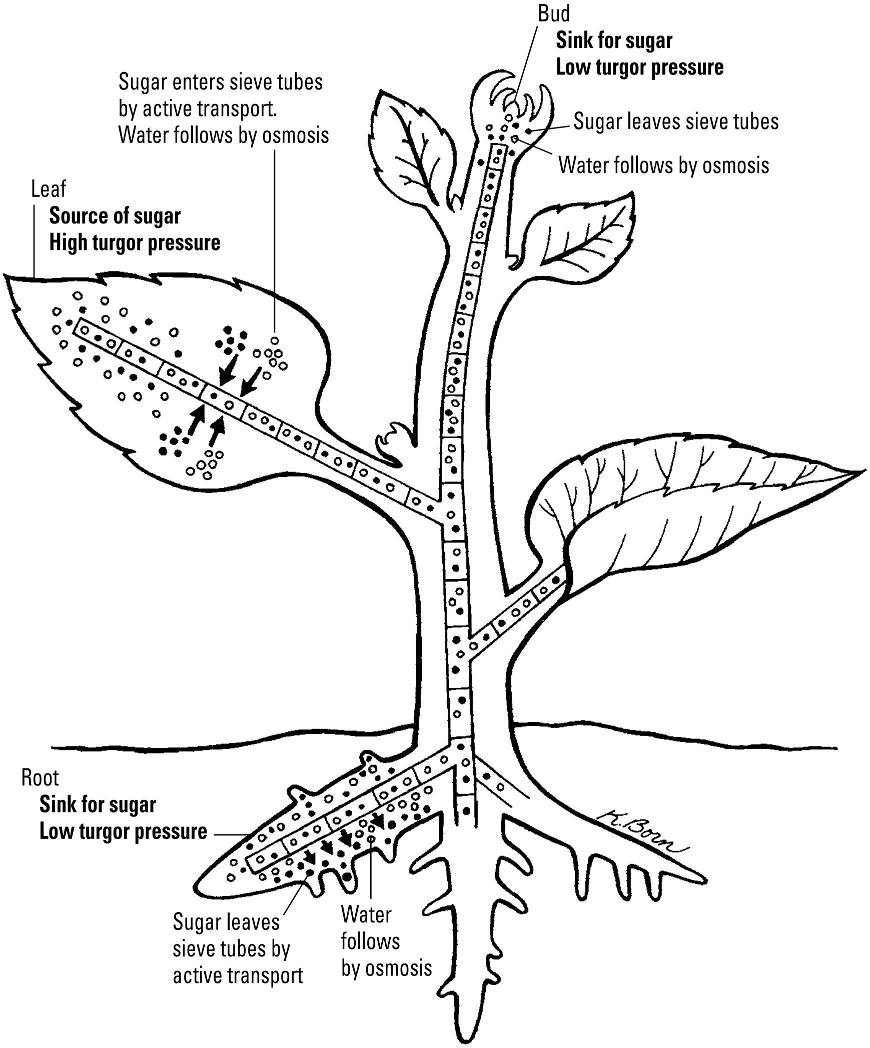

Bud
Sink for sugar
Low turgor pressure
Sugar enters sieve tubes by active transport. Water follows by osmosis
Sugar leaves sieve tubes
Water follows by osmosis
Leaf
Source of sugar
High turgor pressure
Root
Sink for sugar
Low turgor pressure
Sugar leaves sieve tubes by active transport
Water follows by osmosis
K.Born

FIGURE 7-7: The pressure-flow hypothesis explains the movement of sugars through a plant.

IN THIS CHAPTER

- **Comparing types of plant growth**
- **Looking at signal transduction**
- **Exploring the effects of plant hormones**
- **Discovering how plants measure light with phytochrome**

Chapter 8

Regulating Plant Growth and Development

Plants grow and change throughout the year, usually in predictable patterns that reflect their responses to the changing environment. An annual plant might sprout from a seed, grow to maturity, flower, and reproduce all in one growing season. Perennial plants, on the other hand, can take longer to reach maturity and may change their growth and behavior in order to survive periods of cold. This chapter explores how plants use hormones and photoreceptors to regulate their growth and development.

Exploring the Cyclical Nature of Plant Life

People have been studying how plants grow and change throughout the year for as long as there have been people. In places that have seasonal changes, we notice when new plants begin to grow, when leaves break out of their buds, when flowers bloom, and when fruits are ready to harvest (the last piece of information is especially important to people who forage and farm). In the mid-1800s, the botanist Charles Morren named this type of study *phenology*.

REMEMBER

Phenology is the study of the timing of life cycle events of organisms in relation to environmental conditions. Examples of these major *phenophases* include things like initial growth, breaking leaf buds, falling leaves, first flower, and pollen release.

In order for plants to grow and change in response to their environment, they must be able to detect environmental conditions and then respond to them. *Receptors* are chemical structures, usually proteins, that detect signals. For example, plants use receptors called *photoreceptors* to detect changes in light, allowing plants to respond to daily and seasonal changes. When plant receptors detect environmental conditions, they can trigger the release of *plant hormones*, small molecules that can move through the plant body to cause changes in the growth and development of tissues, allowing a plant to continue to grow and change throughout its life cycle.

The Cellular Basis of Plant Growth and Development

As plants grow, they increase in height and weight. While growth results in increased plant size, *differentiation* results in new or more specialized functions of plant structures.

At the cellular level, plant growth results from two different processes:

- **Division growth:** Cell division by meristems produces growth by the addition of new cells.
- **Elongation growth:** Cell elongation produces growth as single cells expand.

Growth that increases the height of plants occurs at the tips of shoots and roots. At the very tip of both roots and shoots, apical meristems produce new cells, creating organized tissues (for more on meristems, flip back to Chapter 2). Just behind the meristematic tissue of both shoots and roots is the elongation zone where most of the elongation growth occurs. As cells elongate, they also mature and become specialized for different functions. As cells mature, they differentiate and change their structure to suit their function. After cells have differentiated and are mature, they typically no longer grow.

The behavior of plant cells — whether they divide, elongate, or differentiate — is controlled by plant hormones, which are released in response to the state of the plant's environment.

Receiving signals

In order for a cell in a plant tissue to respond to a hormone, it must have a *receptor* for that hormone. Once a hormone binds to the receptor, the receptor relays the signal to the inside of the cell in a process called *signal transduction.*

These three main steps occur during signal transduction in a plant cell:

1. **Reception: A hormone binds to a receptor in the plasma membrane of a cell.**
2. **Signal transduction: The part of the receptor that extends into the cell changes, activating molecules inside the cell called *second messengers.***
3. **Induction: Second messengers cause a change in the behavior (based on chemical reactions) of the cell.**

Responding to signals

Cells respond to signals like hormones by changing their behavior: They may produce new structures, change their metabolism, or start the process of cell division. Each change requires the cell to use certain proteins and not others.

So, in order for a cell to change its behavior, it must make the right proteins for the new task at hand. The instructions for making proteins are written in the genetic code of DNA and contained in sections of chromosomes called *genes*.

When cells need to make a new protein for a particular task, they copy the instruction in the gene for that protein and then make the protein using the cell's ribosomes. So, if a cell receives a signal to change its behavior, it can respond by accessing new genes and building new proteins.

REMEMBER

Gene regulation is the process that causes cells to access certain genes and not others — or as scientists say, to turn genes on and off. Ultimately, signals like hormones cause changes in behavior because they cause changes in gene regulation. After the hormone binds to its receptor, the activated second messengers cause genes to be turned on or off in the cell. Thus, hormones control growth and differentiation of plant cells. *Development* is the process of growth and differentiation of cells into tissues, then tissues into organs, and organs into organisms.

Sending Signals with Plant Hormones

Five major groups of hormones control the development of plants (other plant hormones, like brassinosteroids, can also affect plant development). Table 8-1 summarizes the origin and major effects of each of these groups. The following sections add details on how these hormones coordinate specific plant responses.

TABLE 8-1 Five Major Groups of Plant Hormones

Hormone Group	Origin in Plant	Effects on Plant
Auxins	Produced by apical meristems, buds, and young leaves	Phototropism, gravitropism, apical dominance, inhibition of leaf abscission, flower initiation, sex determination, fruit development
Cytokinins	Mainly produced in roots and exported upward into plant	Cell division, cell differentiation, lateral bud development, stimulate cotyledon growth, delay of senescence, opening of stomata
Gibberellins	Produced by apical meristems, young leaves, and embryos	Cell elongation, rapid stem elongation, breaking of dormancy, promotion of flowering
Abscisic acid	Produced in plastids so found in green tissues, also found in fleshy fruits	Growth inhibition, closing of stomata, delay of seed germination
Ethylene	Produced by fruits, flowers, seeds, leaves, and roots	Ripening of fruit, leaf abscission, senescence, initiation of elongation and bud development

Auxins

Auxins were the first plant hormones to be discovered, and they influence many aspects of plant growth and development. Auxins were discovered when scientists investigated the ability of oat seedlings to bend toward the light, a response called *phototropism*.

A Dutch botanist named Frits Went set out to find out what exactly in the young oat seedlings was causing them to bend toward the light. Figure 8-1 shows the results of his experiments:

1. **Went cut off the tips of young oat seedlings, called *coleoptiles*, and placed the shoot tips on a slab of a gelatin-like material called agar.**

   If the tips of the oat seedlings were making a chemical that influenced shoot growth, the chemical could soak into the agar.

2. **After letting the seedling shoot tips rest on the agar for a few hours, he cut the agar up into little squares and then tested how beheaded seedlings would respond to the agar squares.**

   Putting the agar squares on top of a beheaded seedling would be a way of applying chemicals from the shoot tips to the seedlings.

3. **If he put the agar square directly on top of a beheaded seedling, the seedling grew straight up.**

   These seedlings behaved like normal seedlings, which showed that the agar blocks could replace the function of the missing shoot tips.

4. **If he put the agar square off to one side of a beheaded seedling, the seedling curved away from the agar square.**

   By putting the agar square off to the side, Went was applying the chemicals to just half of the beheaded seedling. This way, he could compare the behavior of the two halves. The cells in the half that were exposed to the chemical grew more quickly than the cells in the other half, causing the side of the seedling under the agar to get longer, faster. This made the shoot tip curve toward the side that didn't get the chemical — in other words, away from the side with the agar square.

Went's experiment showed that the coleoptile tips were making something that could diffuse into the agar and that was causing the tips to bend. Went named the substance *auxin* for a Greek word that means to grow.

Apical dominance

If you've ever pinched the top off a plant in order to encourage the side branches to grow, then you already know something about apical dominance. *Apical dominance* is the tendency of most plants to grow upward more than outward. Apical dominance results from the ability of apical meristems to inhibit lateral buds.

Botanists demonstrated that the inhibitory effect on lateral buds is due to auxin by doing a simple experiment. First, they pinched the tips off stems and showed that the lateral buds began to grow. Then, they pinched the tips off stems and replaced the tips with wax plugs that contained auxin. The lateral buds remained dormant just as if the apical buds were still present.

As long as an active apical meristem is located near lateral buds, the lateral buds remain dormant. If you pinch off the apical meristem, then the inhibition disappears, and the lateral buds begin to grow. So, if you want bushier house plants, you can pinch off the ends of the growing branches to encourage side branches to grow. As a plant gets taller, the lower lateral buds get further from the source of auxin, so they're not inhibited as strongly and may start to grow. In trees such as conifers, atypical dominance often leads to a triangular Christmas-tree appearance.

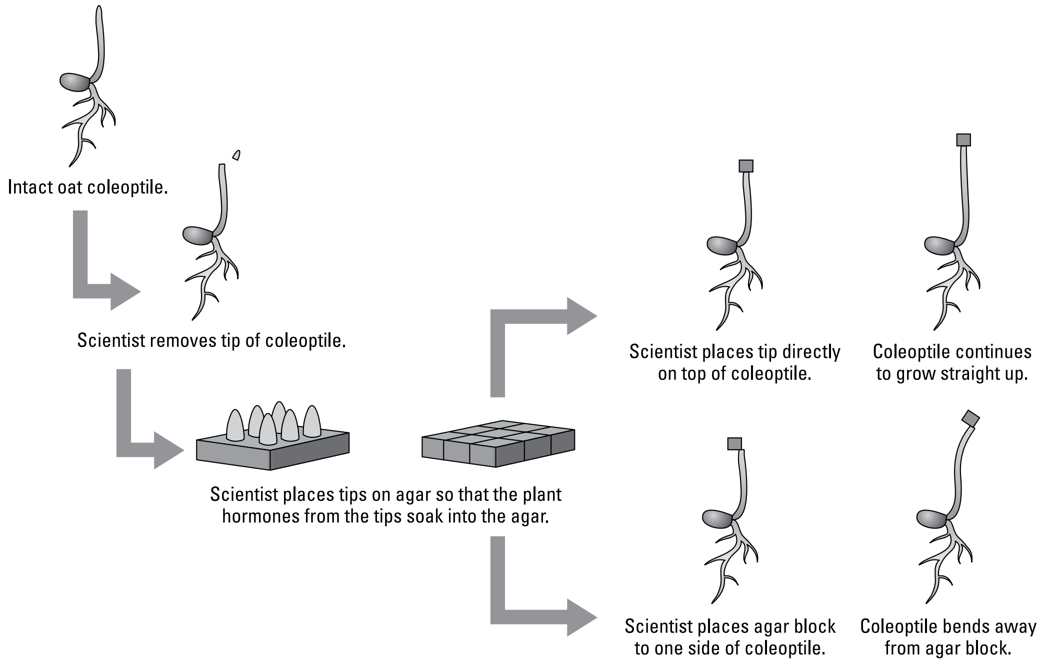

Intact oat coleoptile.
Scientist removes tip of coleoptile.
Scientist places tips on agar so that the plant hormones from the tips soak into the agar.
Scientist places tip directly on top of coleoptile.
Coleoptile continues to grow straight up.
Scientist places agar block to one side of coleoptile.
Coleoptile bends away from agar block.

FIGURE 8-1: Went's experiments on oat coleoptiles.

Cell elongation

Auxin targets cells in the elongation zone of a stem, enabling them to stretch. Botanists demonstrated this effect of auxin by cutting the elongation zone out of stems. If they gave the stem pieces sugar, water, and minerals, they could keep them alive, but the stem pieces wouldn't grow. But when the scientists added auxin to the mix, elongation occurred.

Many botanists believe that auxin plays a role in cell elongation according to a process called the *acid-growth theory:*

1. **Auxin activates a membrane transport protein called ATPase and causes that protein to pump hydrogen ions (H^+) into the cell wall.**
2. **As H^+ concentration increases, the pH of the cell wall decreases and the cell wall becomes acidic.**
3. **The acidic conditions in the cell wall cause loosening of the bonds that hold the wall together, for example by favoring the activity of enzymes that break bonds in the hemicellulases in the wall.**
4. **After acidification loosens the cell wall, it's easier for cells to expand.**
5. **Auxin also activates growth genes that are required for sustained cell elongation to occur.**

Cytokinins

Like auxins, cytokinins have many effects on plant growth and development. They were first discovered because of their ability to stimulate cell division and trigger the production of the cork cambium in woody plants.

One of the most interesting aspects of cytokinins is the balancing relationship they have with auxins. Several growth responses in plants depend not just on the presence or absence of these two hormones, but on the ratio of the two.

Botanists have experimented with these responses by growing plant tissues in the laboratory in a process called *tissue culture.* Pieces of mature stems, leaves, or roots are cut from plants, placed on agar and nutrients, and then exposed to different ratios of auxin to cytokinins:

- If the amount of auxin and cytokinin are equal, the stem pieces will grow into a disorganized blob of cells called a *callus.*
- If the amount of auxin is high and the cytokinins are low, then the plant tissue develops roots.

- If the amount of auxin is low and the cytokinins are high, then the plant tissue develops shoots.

Tissue culture demonstrates that the correct ratio of auxins and cytokinins is essential for plants to develop their organs in the right places. If you've ever taken a plant cutting and placed it in a glass of water to get it to root, you've tested this idea. By taking a cutting, you separate a piece of shoot from the roots, creating a little plant that had a high auxin to cytokinin ratio. The imbalance in the hormones signals the plant about what it's missing, and it responds by making new roots!

REMEMBER

Auxins are produced primarily in shoot apical meristems, while cytokinins are produced primarily in root apical meristems.

Gibberellins

Gibberellins are probably best known for their ability to stimulate cell division in the internodes of plants. If you've ever grown lettuce or cabbage in your garden, you've probably seen the effect of gibberellin. In spring, these plants form lots of leaves very close together, forming a rosette or head of leaves. These rosettes form because the internodes between the leaves are very short. But then, as the days get longer and warmer, your cabbages and lettuces may suddenly bolt, rapidly sending up a flowering stem that has long internodes between the leaves. The longer days and warmer weather triggers the production of gibberellins, leading to the change in growth of your garden plants.

Some plants, such as peas and beans, produce dwarf varieties that are short because they completely lack the ability to make this hormone. When gibberellin is applied to these dwarves, their internodes grow rapidly, and they look like their nondwarf relatives. For example, bush beans that you might grow in your garden can be transformed into pole beans by the application of gibberellin.

Abscisic acid

Abscisic acid inhibits plant growth and triggers bud dormancy. In fact, commercial growers apply abscisic acid to nursery plants in order to trigger dormancy before shipping so that buds are less likely to be damaged in transit.

When leaves are under water stress, they increase production of abscisic acid. The abscisic acid interferes with the transport of potassium ions in guard cells, causing them to become flaccid and close the stomata (for more on the movement of water through plants, see Chapter 7). By closing the stomata, the abscisic acid helps protect the plant from further water loss.

Ethylene

Ethylene is a gas that's best known for its ability to trigger ripening in fruit. People have suspected the existence of ethylene since ancient times: The ancient Egyptians gassed figs to speed up their ripening, and the Chinese burned incense in rooms with ripening pears. Today, commercial growers of many fruits, such as bananas, mangoes, and melons, harvest the fruits when they're green so that they'll be firm for shipping and then gas them with ethylene to give them a ripe color before selling them.

Ethylene also plays an important role in other growth responses, such as triggering leaf abscission, which is the release of leaves from trees.

Which Way Do I Go?: Plant Movements

Plants may not be able to get up and go, but they do move. Plants can change the angle of their leaves so that the leaves track the movement of the sun in the sky. Plants can bend their stems toward the light, too, and their roots grow downward in response to gravity. Some plants even have quick movements, like those of the Venus flytrap, which enable them to respond to the presence of predators and prey.

Growth movements (tropisms)

REMEMBER

One type of plant movement — a *tropism* — is a directional movement that results from growth in a particular direction. These growth movements occur in response to elongation of selected cells. Plants exhibit tropic growth in response to many signals, including light, gravity, chemicals, and temperature. As examples, three of the best studied tropisms are

- **Phototropism:** If light shines on a plant from one side, the plant shoot will exhibit *positive phototropism,* and bend toward the light. If you've ever grown plants near a window, you've probably seen evidence of this particular tropism. Photoreceptors in the tips of plant shoots absorb blue light. Signal transduction occurs, leading to a greater production of auxin on the dark side of the shoot. Auxin promotes cell elongation, so the cells on the dark side elongate faster than the cells on the light side and the shoot bends toward the light.
- **Geotropism (gravitropism):** Plant roots grow toward the pull of gravity, so they show *positive geotropism.* Plant shoots, on the other hand, grow away from gravity, showing *negative geotropism.* You can test this by laying a plant on its side. After a while, the shoots will turn and grow upward, while the roots

will turn and grow downward. A great deal of evidence supports explanation for geotropism outlined by the *starch- statolith hypothesis*. According to this hypothesis, plants sense the pull of gravity on amyloplasts located in the cells of the root cap and close to the vascular bundles in shoots. The amyloplasts get pulled by gravity so that they collect on one side of the cell that contains them. Auxin is produced in response to the pressure of the amyloplasts, and transported to the side of the root or shoot where the amyloplasts have accumulated. In shoots, auxin stimulates cell elongation, so the side of the shoot where the amyloplasts have accumulated grows faster, and the shoot curves up. In roots, high concentrations of auxin actually inhibit cell elongation, so the side of the root with the amyloplasts grows more slowly than the other side, and the root curves downward.

- **Thigmotropism:** I like to think of this tropism as "thing-mo-tropism" because it's curvature in response to touching a thing. One of the most familiar examples of thigmotropism is when a climbing plant, such as a pea or a vine, curls a tendril around a support. Because these plants curve toward the solid surface, they exhibit *positive thigmotropism.* Roots, on the other hand, will curve away from solid objects like the rocks that they encounter in the soil, so they exhibit *negative thigmotropism.* The mechanisms for thigmatropism are still being investigated, but some things are known. Some extremely rapid curvature responses result from changes in turgor pressure. Prolonged curvature results from differential growth, where one side of the shoot or root grows more rapidly than the other. The touch signal is received by epidermal cells, and then signal transduction results in differential growth of the shoot or root. Unlike phototropism and gravitropism, thigmatropism does not seem to be controlled by auxin.

Turgor movements

REMEMBER

Turgor movements occur in response to changes in turgor pressure in certain cells. Whereas growth movements take some time because the plant actually has to grow, turgor movements are very rapid. For example, some tendrils exhibit rapid coiling around a solid support, positive thigmatropism, due to turgor movements, followed by continued curved growth due to growth movements. (For more details on curved growth, see the earlier "Growth movements" section.)

During turgor movements, cells rapidly lose their turgor pressure and collapse, causing the plant to fold around those cells. Here's what scientists think is happening to cause these responses in tendrils:

1. **Touch receptors sense the pressure of a solid object.**
2. **Signal transduction occurs, causing cells near the touch stimulus to export potassium ions (K^+) outside the cells, thus making the environment hypertonic to the plant cells.**

3. **Water leaves the plant cells, following the K^+, and the cells collapse, causing the plant to fold.**

In addition to curving tendrils, turgor movements also occur in *Mimosa pudica*, which is sometimes called the sensitive plant or the shy plant. If you run your fingers along the leaves of this plant, they fold up immediately. At the base of each leaflet is a swollen structure called a *pulvinus*. When you touch the leaves of the sensitive plant, the signal is relayed to the pulvinus. Cells on one side of the pulvinus lose their turgor pressure, causing the leaves to fold together.

What Time Is It?: Sensing the Seasons

Plants know when to flower, when to go dormant, and when to germinate from their seeds. Both temperature and light play a role in the ability of plants to track the changing days and the changing seasons. Many seasonal responses of plants rely upon the activity of a photoreceptor called phytochrome.

REMEMBER

Phytochrome is a photoreceptor that detects the presence of two specific kinds of light: red light (660nm) and far-red (730nm) light. (To see how these types of light fit into the electromagnetic spectrum, see Chapter 5.) Red light is available to plants only during the day when the sun is shining, but far-red light is available both day and night.

As phytochrome absorbs light, it changes between two forms: P_{red} (P_{r}) and $P_{\text{far-red}}$ (P_{fr}). You can think of phytochrome as a molecular switch that flips back and forth between its two forms.

Figure 8-2 illustrates how phytochrome changes form:

- When P_{r} absorbs red light, it's rapidly converted to P_{fr}.
- When P_{fr} absorbs far-red light, it's rapidly converted to P_{r}.
- If a plant is in the dark, P_{fr} will slowly convert back to P_{r}.

REMEMBER

P_{fr} is the active form of phytochrome. In other words, the presence of P_{fr} in plant cells is what triggers responses. P_{r} is inactive.

Phytochrome helps regulate a number of plant responses, including flowering, seed germination, *etiolation* (growing tall in response to shade), as well as plastid and pigment production.

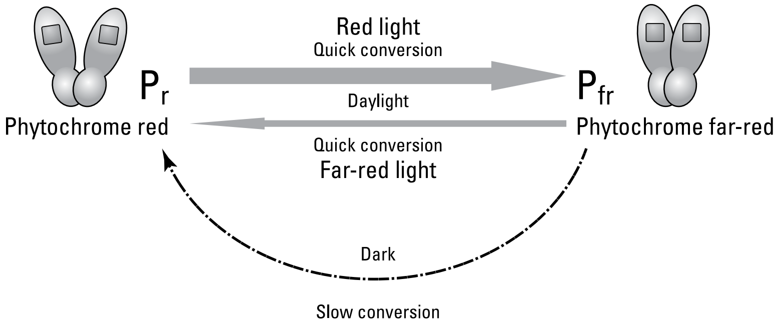


FIGURE 8-2: Conversion of phytochrome between its two forms: P_{red} and $P_{far\text{-}red}$.

Flowering

REMEMBER

Many flowering plants use phytochrome to figure out when to make their flowers. Plants use phytochrome to measure the *photoperiod*, which is the length of the light period.

When the sun is shining, phytochrome absorbs the sunlight. As a result, most of the phytochrome in plant cells is converted to the P_{fr} form. But when it's dark, the P_{fr} slowly converts back to P_r. So, the longer the night, the more P_{fr} that gets converted back to P_r. Based on the ratio of P_{fr} to P_r, plants can essentially tell how long the nights are relative to the days.

REMEMBER

Plants detect the changing length of the dark period, called the *skotoperiod*, as measured by the conversion of P_{fr} to P_r, in order to measure the time of year.

Botanists divide plants into three categories based on their flowering preference:

- **Short day plants** flower as the nights get longer and the days get shorter — in other words, in the fall or spring.
- **Long day plants** flower as the nights get shorter and the days get longer — in other words, in the summer.
- **Day neutral plants** flower when they're mature, regardless of photoperiod.

Botanists did experiments to figure out whether it was the length of the photoperiod or the skotoperiod that was important to plant flowering. They used soybean, which is a short-day plant:

- Soybeans that were given 16 hours of light and 8 hours of dark remained vegetative and did not produce flowers.

- Soybeans that were given 8 hours of light and 16 hours of dark produced flowers.
- Soybeans that were given 8 hours of light and 8 hours of dark remained vegetative.
- Soybeans that were given 16 hours of light and 16 hours of dark produced flowers.
- Soybeans that were given 8 hours of light, 8 hours of dark, then 5 minutes of light, and then 8 more hours of dark remained vegetative.

REMEMBER

From these experiments, botanists learned that as long as plants experience a continuous dark period that's longer than their unique critical period of darkness, they will flower.

These types of experiments led to the *hourglass model of photoperiodism.* According to this model:

1. **Plants detect the length of the skotoperiod with the phytochrome in their leaves.**
2. **The changing ratios of P_r and P_{fr} signal to the plant whether the nights are getting longer or shorter, thus indicating the season of the year.**
3. **When the plant detects the proper season, the plant leaves relay a signal to the meristems, causing the plant to build reproductive buds (flowers) rather than vegetative buds (leaves).**

The ability to flower can also be affected by the maturity of the plant and by the temperature of the environment. Some plants must grow in a vegetative state for a certain period of time before flowering is possible, regardless of the photoperiod. Other plants must experience *vernalization,* which is exposure to a cold period for a certain length of time, before they'll respond to their correct photoperiod.

Circadian rhythm

All living things have *endogenous rhythms,* rhythms that persist under constant environmental conditions. When organisms are placed in constant environmental conditions like continuous darkness, their rhythms may become irregular, but when organisms are exposed to natural cycles of light and dark, their rhythms become very regular.

REMEMBER

Circadian rhythms are endogenous rhythms that cycle approximately every 24 hours. Some examples of circadian rhythms are cycles of melatonin in your body, animal activity, such as that of cockroaches that run at night, and leaf movements of plants that extend their leaves outward during the day and then lower them at night. Circadian rhythms are set by proteins called *clock proteins* whose concentrations in cells rise and fall at regular intervals.

Recent research suggests that circadian rhythms may play a role in flowering. The mustard plant *Arabidopsis thaliana* is a long day plant that produces flowers in the summer. *A. thaliana* uses phytochrome and another photoreceptor called *cryptochrome*, which responds to blue light, to measure the length of the photoperiod and time its flowering. Botanists have discovered that these photoreceptors interact with the circadian rhythm of an important control protein called CONSTANS that's needed to trigger flowering.

Seed germination

Seeds are dormant, waiting for the right conditions before they *germinate* or begin to grow.

As seeds develop in the parent plant, seed dormancy is induced by

- The accumulation of abscisic acid, which inhibits growth
- The breaking of connections between the seed and the xylem and phloem of the parent, so that the seed dries out
- The formation of hard, restrictive seed coat
- Increasing levels of acidity in some fruits, such as grapefruit and tomato

To trigger germination, the conditions that promoted dormancy must be reversed:

- A period of cold, wet weather will cause abscisic acid to break down and will increase the levels of gibberellin, which will promote germination.
- Damage to the seed coat from the digestive tract of animals or physical cracking from frost may make it possible for the embryo to begin to grow.

Many botanists use the example of grass seeds like those of barley as an example of the early events that occur during seed germination:

1. **Once the seed is released from dormancy, the embryo releases gibberelin.**
2. **The gibberelin travels to a layer of live cells, called the *aleurone layer,* that wraps around the endosperm in the grain.**

   For the structure of a monocot grain, see Chapter 4.
3. **The gibberelin signals the cells in the aleurone to produce the enzyme alpha-amylase.**
4. **The alpha-amylase breaks down the stored starch in the endosperm, converting it to sugars that the embryo can use to begin growing.**

Some seeds, like those of some varieties of lettuce, require light signals in order to germinate. These seeds detect the presence of light using phytochrome. If the seeds are in the dark because they're deep in the soil, the phytochrome will convert from P_{fr} to P_r, and the seeds won't germinate. If you've ever turned over some soil and saw a resulting burst of weed growth, you've seen what happens when light-sensitive seeds receive enough sunlight to convert their phytochrome from P_r to P_{fr}!

3

Making More Plants: Plant Reproduction and Genetics

IN THIS PART . . .

Discover how plants use asexual and sexual reproduction to make new offspring

Investigate how the laws of inheritance determine the characteristics of new plants

Explore how plants have changed through time due to natural selection

Check out some cool plant adaptations to unique environments

IN THIS CHAPTER

- **Comparing asexual and sexual reproduction**
- **Making more cells with mitosis**
- **Producing haploid cells with meiosis**
- **Getting into plant life cycles**

Chapter 9

Greening the Earth: Plant Reproduction

Plants are very versatile in that they can reproduce both asexually and sexually. During asexual reproduction, plants use mitosis to make offspring that are genetically identical to themselves. During sexual reproduction, plants use meiosis to produce haploid cells that eventually lead to the formation of gametes. Plant life cycles are complex because they contain two separate alternating generations — one haploid, and one diploid. In this chapter, I explore the pros and cons of different types of reproduction and present the details on exactly how plants do it.

Reproducing: More Than One Way to Do It

Plants are extremely successful organisms in part due to their reproductive flexibility. People can reproduce only by getting together with a mate, but plants have more options. Although some plants do reproduce sexually, many plants produce offspring all by themselves by growing underground stems or bulbs that generate new shoots or by producing entire new plants from fragments of their stems or leaves.

Asexual reproduction

If you've ever put a plant cutting in a glass of water to get it to root, then you've seen firsthand that some plants can reproduce without any help from another plant. New plants that grow from pieces of old plants are called *clones* because they're genetically identical to their parent. (Imagine if you dropped pieces of yourself and they grew into little "mini-me's"!)

REMEMBER

Nearly all plants can do some form of *asexual reproduction*, producing offspring that are identical to themselves (see Figure 9-1). During asexual reproduction, plant cells divide to make exact copies of themselves by a process called *mitosis*.

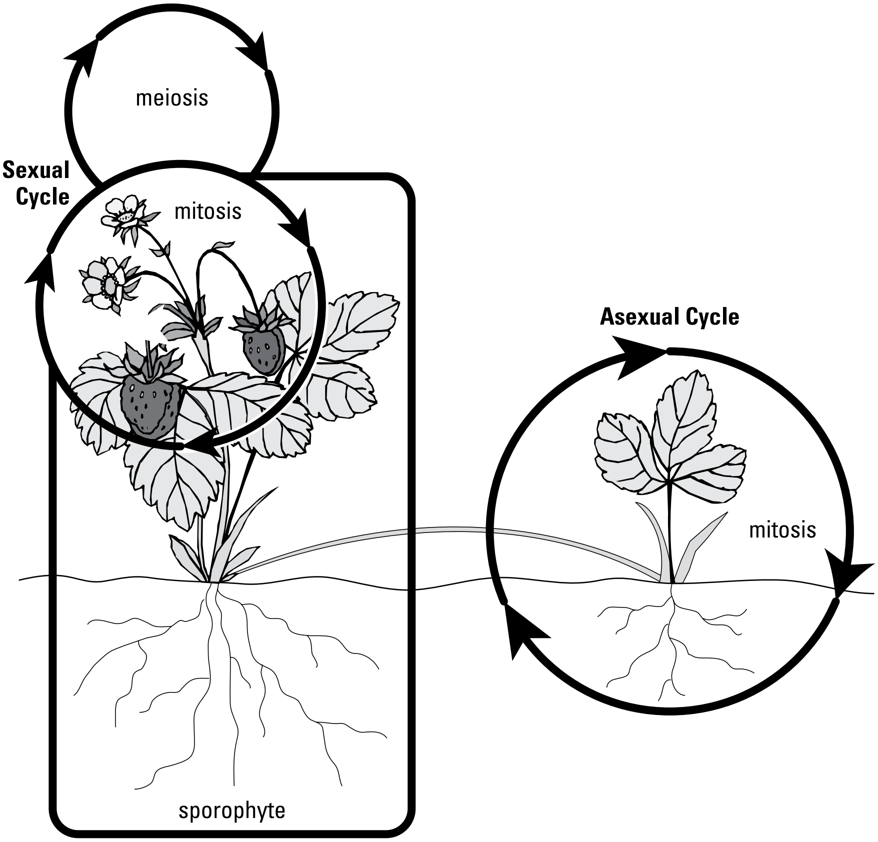


FIGURE 9-1: Asexual and sexual reproduction in a strawberry plant.

STICKING WITH A GOOD THING

Corn is a hugely important agricultural crop in the United States. If you don't believe me, take a walk through your grocery store and read some labels. Almost everything you can find will contain corn or corn products, such as corn syrup and cornstarch. Even the meat likely comes from animals raised on feed that contains corn! Farmers and agricultural scientists have bred corn for years, trying to develop varieties that have high yields, resist pests, or taste really good. One problem that farmers and agricultural scientists face is that even when they get a variety that they really like, sexual reproduction shuffles up the genes so that offspring may not have all the desired qualities. Enter *apomixis,* the process of making a seed or embryo without the bother of finding a mate.

Some plants, including citrus plants and dandelions, can produce seeds without going through the trouble of sexual reproduction. The seeds are genetically identical to the parent and have all the same traits. Some plant breeders have realized the enormous potential of apomixis for crop plants like corn — if apomictic strains could be developed, they would breed true indefinitely.

So, breeders set to work trying to develop apomictic strains of corn. They started by mating corn with one of its relatives, a grass that can reproduce by apomixis. The scientists successfully created a hybrid plant that could reproduce by apomixis, but it wasn't corn. So, they did another 5,000 matings, each time mating the progeny back to corn to create a plant that was more and more corn-like but could still reproduce by apomixis. The breeders were successful, up to a point. They did create apomictic corn, but the yield on the variety is not high enough for commercial purposes.

Other breeders and scientists are very interested in this work, however, because it represents a way we might keep desirable traits in hybrid crop plants. Scientists have continued this research, identifying and manipulating genes that are important to cell division as a way to trigger "synthetic apomyxis." The most successful outcome in a crop plant so far is the development of a strain of hybrid rice that shows a high frequency of apomixis.

Asexual reproduction occurs by a variety of methods in plants and can involve different organs:

- **Stems:** Stems may extend from the parent plant, forming new individuals at intervals. Strawberries, such as the plant in Figure 9-1, reproduce asexually by stolons, whereas potatoes use tubers, daffodils grow from bulbs, and gladioli reproduce by corms. (For the details on these modified stems, refer to

Chapter 3.) In the case of potatoes, the eyes of the potato are actually buds that can grow into new potato stems. The bulbs and corms of daffodil and gladiolus plants get bigger year after year, forming lateral buds that grow into new stems.

- **Roots:** Some plants, such as aspen and poplar trees, send roots out horizontally from the original plant. The horizontal roots grow new stems at intervals, producing large stands of trees that are genetically identical to each other. Other plants, such as dandelion, have a long tap root that can generate new stems if the original stem is damaged.
- **Leaves:** Leaves of the common houseplant *Kalanchoë* form tiny little *plantlets* along the edges. These plantlets can drop to the ground, produce roots, and grow into new individuals. Plants called liverworts make tiny little cups called *gemmae* on the surfaces of their leaf-like bodies. When rain splashes into the cups, clumps of cells break off and scatter, forming new plants wherever they land.
- **Flowers:** Although flowers usually mean sexual reproduction, some plants, such as citrus trees, produce seeds asexually by a process called *agamospermy* (a type of apomixis as described in the nearby sidebar "Sticking with a Good Thing"). During agamospermy, a cell from the parent plant develops into a seed containing an embryo that is a genetic copy of the parent.

REMEMBER

Fragmentation, the process where a plant part breaks off and develops into a new individual, occurs with stems, roots, and even leaves.

Sexual reproduction

Although asexual reproduction is very common in plants, most plants can also mix it up a little by combining their genetic information with another plant to produce offspring that have unique combinations of genetic information.

REMEMBER

Most plants can do asexual reproduction and *sexual reproduction*, where an egg from one plant combines with sperm from another plant to produce offspring that have new combinations of traits. Tulips, for example, reproduce asexually through tulip bulbs, but also reproduce sexually by making flowers, fruits, and seeds.

The most obvious participants in sexual reproduction are the flowering plants — their showy flowers are basically advertising that they're looking for a mate — but more subtle plant sex is happening around you all the time. All the cone-bearing plants, such as pine, spruce, and fir, reproduce sexually, as do flowering trees like maple, oak, and willow. Sex is even going on among the grass and moss under your feet!

Comparing reproductive styles

Both asexual reproduction and sexual reproduction have their advantages:

- **Asexual reproduction rapidly produces copies of a successful organism.**
  - **Advantage:** If the traits of the parent plant are working well in a particular environment, then asexual reproduction will produce more successful organisms without the hassle of finding a mate. In other words, if it ain't broke, don't fix it.
  - **Disadvantage:** If conditions change so that the parent's traits aren't very successful, then all the clones will be negatively impacted at once. Also, small genetic changes called *mutations* that occur in the clones will be passed onto all their offspring. Most mutations have negative impacts on individuals, and asexually reproducing populations collect more and more mutations over time.
- **Sexual reproduction creates individuals with unique combinations of traits, increasing the chances that some offspring will survive.**
  - **Advantage:** Environments change, and individuals come under attack from predators and parasites. The greater the diversity in offspring, the more likely it is that some will have traits that help them survive. And mutations that occur in parents may not get passed on to offspring at all or may get passed to just some offspring, so that some offspring will be free from these mutations.
  - **Disadvantage:** Offspring from sexual reproduction may be more fragile at first than offspring from asexual reproduction. (Think tiny seedling versus new shoot supported by an underground stem.) And, of course, you can't go it alone — sexual reproduction means successfully capturing gametes from another individual.

Copying Cells by Mitosis

Eukaryotic cells divide by mitosis in order to make exact copies of themselves. Plants use mitosis in order to grow, repair tissues, and reproduce asexually.

Mitosis occurs at different rates in different plant tissues. Cells that are part of meristems divide frequently, whereas mature cells in the vascular tissue never divide (in fact, some die at maturity). Other cells may not typically divide, but might divide to repair damage. So, plant cells may spend some time dividing, and some time not dividing.

The dividing phase of eukaryotic cells is called *mitosis*, and the nondividing phase is called *interphase*. The alternating cycle of mitosis and interphase is called the *cell cycle* (see Figure 9-2).

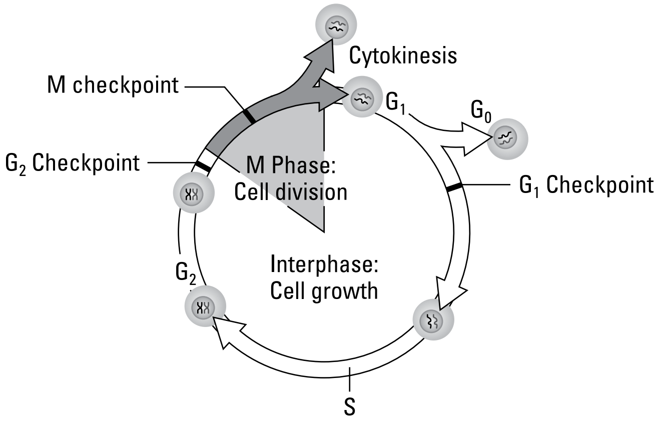


FIGURE 9-2: The cell cycle.

Interphase

Interphase contains three subphases:

- **Gap 1 (G1):** Plant cells that are alive and functioning, but not dividing, are in the phase called *Gap 1 (G_1)*, which is the phase that cells spend most of their time in. A leaf mesophyll cell, for example, will hang out in G_1 doing photosynthesis. If cells get a signal that they're going to divide, they'll grow and double their contents.

  Cells that are going to divide must pass a test, called a *checkpoint,* before they can exit G1 and enter the next phase of interphase.

  Checkpoints are points in the cell cycle where cells check to make sure that everything is proceeding normally. If cells can't pass a checkpoint, repairs will be made, if possible. If not, the cell may be signaled to commit cell suicide, called *apoptosis.* In order for plant cells to pass the G1 checkpoint, they must be big enough, have plenty of nutrients, and have undamaged DNA.

- **Synthesis phase (S phase):** S phase is called the synthesis phase because cells synthesize or make new DNA. During S phase of Interphase, plant cells copy all their chromosomes so that they'll have a complete set to give to a new cell during cell division. Cells attach the two copies of each chromosome together with proteins that stick to a region of the chromosome called the *centromere*.

  After S phase, scientists call chromosomes *replicated chromosomes* because each chromosome is actually made of two identical DNA molecules attached together at the centromere. People usually draw replicated chromosomes as little X's like the ones in Figure 9-3. Scientists call each half of the X a *sister* *chromatid*. The two sister chromatids of a replicated chromosome join together at the centromere. So, before S phase and after mitosis, chromosomes are single DNA molecules, but between S phase and mitosis, replicated chromosomes are double DNA molecules.

- **Gap 2 (G2):** During Gap 2, cells check the work they did during S phase. In order to enter cell division, cells must pass the G_2 checkpoint. The G_2 checkpoint tests whether the cell copied all the chromosomes correctly. If cells can't pass the G_2 checkpoint, they remain in G_2 and try to repair themselves. If they can't repair themselves, they may kill themselves via apoptosis.

Overview of mitosis

Like all eukaryotes, plant cells have multiple *chromosomes,* individual DNA molecules that store their genetic information. Pea plants, for example, have 14 separate chromosomes per cell, whereas some wheat plants have 42 chromosomes and some ferns have up to 1400 chromosomes! When a plant cell divides by mitosis, it has to make sure that each new cell gets a complete set of chromosomes. That's what mitosis is all about: During S phase, plant cells make copies of their chromosomes, so during mitosis, they need to sort carefully and make sure that each of the two new cells gets one of each chromosome.

Mitosis is a carefully controlled process that organizes and separates the chromosomes correctly. After the cells separate the chromosomes and build new nuclei, they divide their cytoplasm by *cytokinesis* to form two distinct cells.

The cell structure that separates the pairs of chromosomes is the *mitotic spindle.* The mitotic spindle is made of microtubules, which are cytoskeletal proteins. *Spindle fibers* of microtubules attach to the chromosomes in order to push and pull them during mitosis.

The four phases of mitosis (refer to Figure 9-3) have unique events that contribute to the careful sorting of the chromosomes:

- **Prophase:** During interphase, the DNA is uncoiled, and the chromosomes aren't visible, even under a microscope. During prophase, cells tightly coil their chromosomes, making the chromosomes easier to move around. Coiling of the chromosomes, called *condensation,* also makes the chromosomes visible under a microscope.

  During prophase, cells break down their nuclear membrane so that the mitotic spindle can reach into the center of the cell and attach to the chromosomes. Cells also break down their *nucleoli,* the dark staining regions in the nucleus that contain the materials for ribosome synthesis. Plant cells can have multiple nucleoli per nucleus. Some scientists separate the events from the breaking down of the nuclear membrane up to the lining up of the chromosomes into a separate phase, called *prometaphase*.

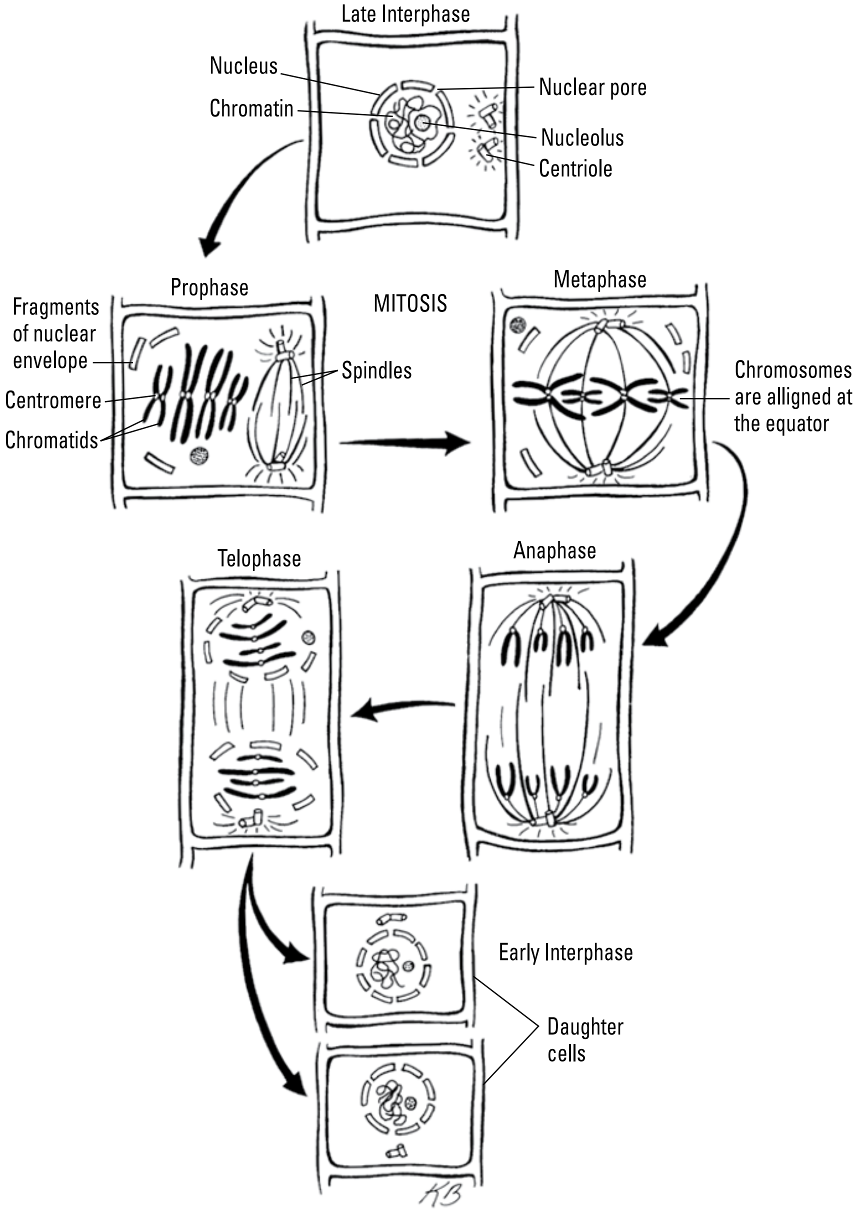

Late Interphase
Nucleus
Chromatin
Nuclear pore
Nucleolus
Centriole
Prophase
MITOSIS
Metaphase
Fragments of nuclear envelope
Centromere
Chromatids
Spindles
Chromosomes are alligned at the equator
Telophase
Anaphase
Early Interphase
Daughter cells
KB

FIGURE 9-3: The process of mitosis and interphase.

- **Metaphase:** During metaphase, cells organize the chromosomes by lining them up in the middle of the cell, halfway between the two poles of the mitotic spindle. At the *metaphase checkpoint,* cells make sure that all the replicated chromosomes are attached to the mitotic spindle. Cells can't continue through mitosis unless they pass the metaphase checkpoint.
- **Anaphase:** During anaphase, cells separate the replicated chromosomes so that each sister chromatid goes to opposite sides of the cell. Cells separate the identical sister chromatids carefully to ensure that each new cell will get one. After the sister chromatids separate from each other, scientists call them chromosomes again.
- **Telophase:** Telophase wraps up mitosis by reversing the events of prophase. During telophase, cells uncoil their chromosomes, reform their nuclear membranes and nucleoli, and break down the mitotic spindle.

Cytokinesis

After a plant cell separates the sister chromatids and builds new nuclear membranes to create two nuclei, it divides its cytoplasm into two parts by forming a new plasma membrane and cell wall down the middle of the cell. Figure 9-4 shows how cytokinesis works in a plant cell:

- A cytoskeletal structure called a *phragmoplast* moves small vesicles containing cell wall material (pectin and hemicelluloses) into a line in the middle of the cell.
- The vesicles fuse together, bringing together the vesicle membranes and the wall material that was inside the vesicles. The vesicle membranes form the new plasma membranes for each cell. The wall material joins together to form the *cell plate*. The two new cells then secrete cellulose and other materials to build a primary cell wall on either side of the cell plate, which is now called the middle lamella. (For details on cell wall structure, go to Chapter 2.)

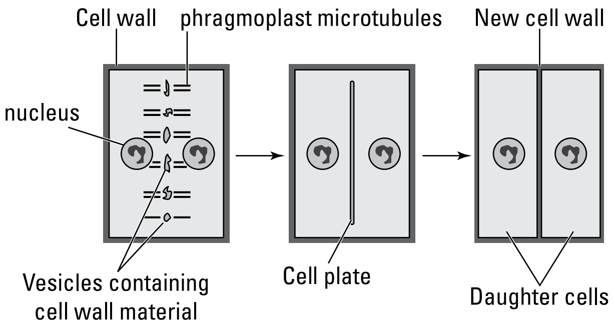

Cell wall
phragmoplast microtubules
New cell wall
nucleus
Vesicles containing cell wall material
Cell plate
Daughter cells

FIGURE 9-4: Cytokinesis in a plant cell.

Reproducing Sexually with Meiosis

Like all sexually reproducing organisms, plant cells divide by meiosis to produce cells that have half the genetic information of the parent.

Counting chromosomes

Each organism has a unique set of chromosomes and each chromosome in the set contains different genes. You may know that you have 46 chromosomes in each cell, and that this represents two sets of 23 chromosomes: 23 that you got from your biological mother and 23 that you got from your biological father. Like animals, plants have two sets of chromosomes in each cell at some point in their lives. For example, a pea plant growing in your yard has 14 chromosomes per cell, representing two copies each of seven different types of chromosomes ($2 \times 7 = 14$). For humans, a complete set of chromosomes is a set of 23 unique chromosomes; for peas, a set contains one each of the seven different types.

REMEMBER

Keeping track of chromosome sets can get confusing, in part because scientists have a whole vocabulary to go along with cell division and changing numbers of chromosomes. These changes are fundamental to plant life cycles, so here are a few tips to help you along the way:

- **Scientists call one complete set of chromosomes the *haploid number* of chromosomes, represented by the letter *N*.** So, the haploid number of chromosomes in peas is seven chromosomes ($N = 7$). Each of the seven chromosomes contains different types of genetic information, and each is essential for normal development of a pea plant. Pea gametes (sperm and egg) are haploid because they have seven chromosomes, or one of each kind, per cell.
- **Scientists call matching pairs of chromosomes from the organism's two parents, containing the same kinds of genes, *homologous chromosomes*.** When two haploid pea gametes (7 chromosomes each) fertilize each other, they create a zygote with 14 chromosomes, two each of the seven different kinds ($2N = 14$ — or, in other words, seven pairs of homologous chromosomes). Each pair of homologous chromosomes contains the same kinds of genes.
- **Cells with two complete sets of chromosomes are *diploid*, represented as 2N.** Diploid cells divide by meiosis to produce haploid cells. Diploid cells can't just pile up all their chromosomes and randomly split them in half, because then the chromosomes wouldn't be sorted into sets. A haploid cell has to have a complete set in order to be normal. So, the whole point of meiosis is to

carefully sort the sets of chromosomes to make sure haploid cells are truly haploid — that is, they have one complete set of chromosomes.

- **Scientists call the number of chromosome sets in a cell its *ploidy*.** Cells in certain plant tissues can have three or four sets of chromosomes, making them triploid, tetraploid, and so on. Some plants are *polyploid,* which means they have many sets of chromosomes per cell. One polyploid fern, *Ophioglossum*, has 1,200 chromosomes per cell!

WARNING

In plants, the products of meiosis are spores, not gametes that are produced by meiosis in animals.

Spores grow into multicellular haploid gametophytes, which then make haploid gametes by mitosis. That way, when sperm and egg join to form a zygote, the new sporophyte plant that develops will have the normal diploid number of chromosomes for that species.

Following the plan

Meiosis occurs as part of the cell cycle (refer to Figure 9-2), just like mitosis. In fact, meiosis has many similarities to mitosis:

- Cells that are going to undergo meiosis receive a signal that causes them to leave G_1 of interphase and enter S phase.
- During S phase, the cells copy all the chromosomes, creating replicated chromosomes that have identical sister chromatids attached at the centromere.
- The cells then proceed through G_2 and into meiosis.
- During meiosis, the mitotic spindle moves the chromosomes and sorts them in similar ways as it does during mitosis. Scientists even use the same terms — prophase, metaphase, anaphase, and telophase — to describe the movements of the chromosomes.

Doubling your stuff and then reducing it twice

Cells divide by meiosis to cut the amount of DNA in the cell by half to make haploid cells. However, before meiosis occurs, cells double their DNA during S phase. So, in order to get the DNA down to the haploid amount, meiosis includes two divisions. (If you start with double DNA and you want to get to half, you have to divide twice — once to get from double DNA to single DNA, then again to get to half.) Figure 9-5 shows the two divisions of meiosis, called *meiosis I* and *meiosis II*, occurring as part of normal meiosis.

TIP

The details of meiosis may seem less overwhelming if you remember the purpose of each division:

- Meiosis I separates the pairs of homologous chromosomes.
- Meiosis II separates sister chromatids.

The events of meiosis I

The phases of meiosis I have many similarities to the phases of mitosis. Figure 9-5 shows the major events of each phase:

- **Prophase I:** Prophase I includes the same major events of prophase of mitosis. Cells in prophase I coil up their chromosomes and break down their nuclear membrane and nucleoli. During prophase I, homologous chromosomes find each other and pair up. The two replicated chromosomes of each pair actually stick together, forming a structure called a *tetrad.* Tetrads have four arms because each replicated chromosome has two sister chromatids.

  While homologous chromosomes are stuck together in tetrads, they can exchange small pieces of DNA in a process called *crossing-over* (see prophase I in Figure 9-5). Crossing over leads to new combinations of genetic material in the chromosomes increasing the diversity in offspring. This increase in diversity is one of the advantages of sexual reproduction.
- **Metaphase I:** The spindle pushes the homologous pairs of chromosomes to the middle of the cell. The major difference between metaphase I of meiosis and metaphase of mitosis is that chromosomes line up in pairs during metaphase I, and they line up as individuals in metaphase of mitosis.
- **Anaphase I:** Spindle fibers shorten toward opposite sides of the cell, pulling the pairs of homologous chromosomes apart so that one chromosome from each pair goes to opposite sides of the cell.
- **Telophase I:** Cells reform nuclear membranes creating two nuclei and break down the spindle. After telophase I, the two nuclei are haploid because they only have one of each type of chromosome. Cells divide their cytoplasm by cytokinesis, resulting in the formation of two cells.

After meiosis I is complete, both cells proceed directly to meiosis II without going through the stages of interphase.

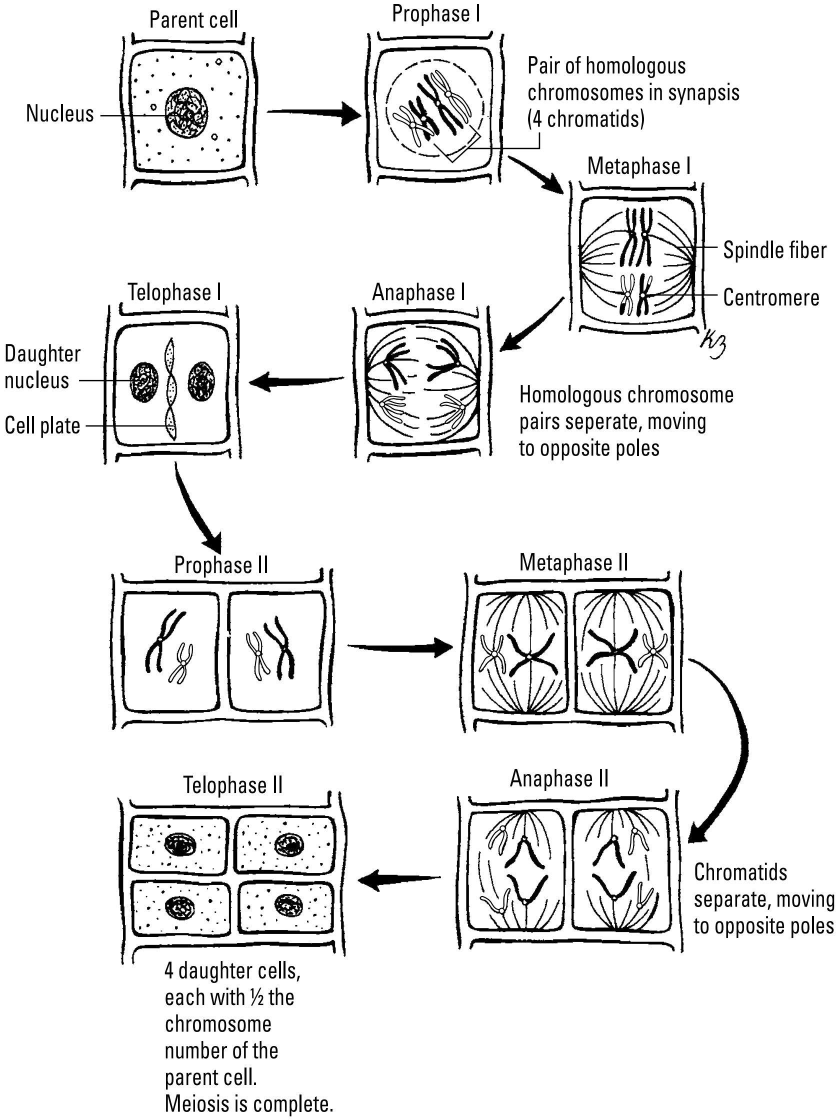

Parent cell
Nucleus
Prophase I
Pair of homologous chromosomes in synapsis (4 chromatids)
Metaphase I
Spindle fiber
Centromere
Telophase I
Daughter nucleus
Cell plate
Anaphase I
Homologous chromosome pairs seperate, moving to opposite poles
Prophase II
Metaphase II
Telophase II
Anaphase II
Chromatids separate, moving to opposite poles
4 daughter cells, each with ½ the chromosome number of the parent cell. Meiosis is complete.

FIGURE 9-5: The events of meiosis.

The events of meiosis II

Meiosis II separates the sister chromatids of each replicated chromosome and sends them to opposite sides of the cell. Once again, the cells pass through several phases similar to those of mitosis and meiosis I (compare Figures 9-3 and 9-5):

- **Prophase II:** Cells reform the mitotic spindle and attach it to the chromosomes. If nuclear membranes formed during telophase I, they break down again.

- **Metaphase II:** Spindle fibers push the replicated chromosomes to the center of the cell where they form a line. *Tip:* The major difference between metaphase II of meiosis and metaphase of mitosis is that the number of chromosomes in metaphase II is only half that of metaphase of mitosis.
- **Anaphase II:** Spindle fibers shorten, pulling sister chromatids apart so they move to opposite sides of the cell.
- **Telophase II:** Cells complete formation of the haploid cells by reforming the nuclear membranes and nucleoli and uncoiling their chromosomes. Cytokinesis occurs in both cells, forming a total of four haploid cells.

Considering Alternation of Generations

Plant life cycles are considerably more complicated than animal life cycles. In animals, meiosis produces haploid cells called gametes that don't last very long on their own. Animal gametes fuse with other gametes, returning the chromosome number back to diploid.

TIP

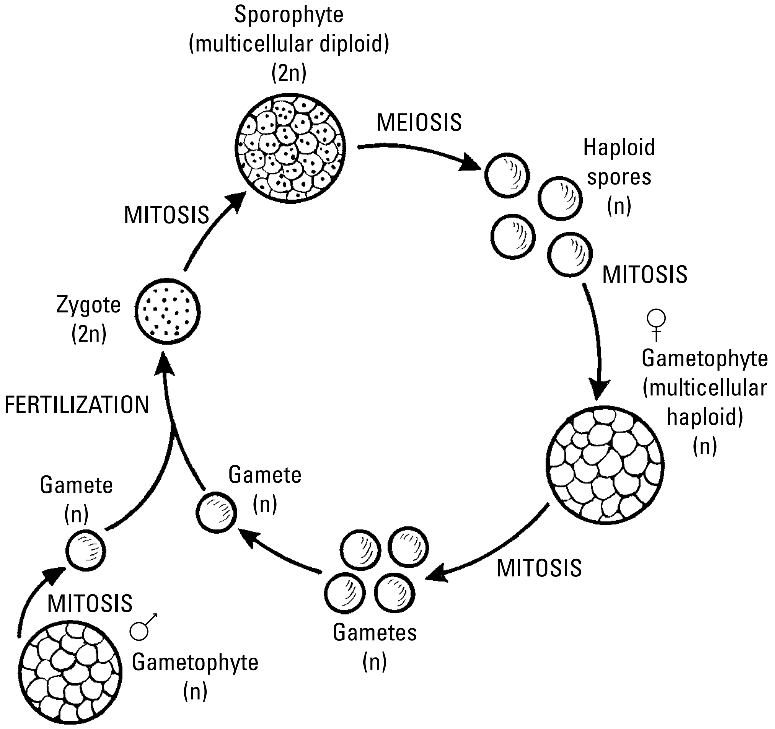
It can be hard for people to relate to plant life cycles because plants do something humans don't do — they produce two different generations within one life cycle, whereas people and all other animals produce one.

To help you relate to the plant life cycle, here's a comparison between people and plants:

- **People:** An individual person is like a plant sporophyte because they have a double copy of the genetic information. When people reproduce sexually, cells in their body undergo meiosis to produce sperm or egg. Sperm and egg get together and a new individual is produced. So, if scientists talked about people in plant terms, people would go from sporophyte (parent) to gametes (egg and sperm) and right back to sporophyte (offspring).
- **Plants:** Plant sporophytes produce reproductive cells through meiosis, but they don't go straight to egg and sperm. Instead, the cells produced by meiosis (the spores) grow for a while by mitosis, making a unique plant structure (the gameteophyte), which eventually gets around to making egg and sperm. If scientists talked about plants in people terms, it would be like

the parents made an egg- or sperm-like cell that grew to have a little life of its own — maybe even as a separate individual — and then that little gametophyte makes the sperm and egg, which join together to make a new sporophyte.

Figure 9-6 shows how plant life cycles actually have two separate generations:



Sporophyte
(multicellular diploid)
(2n)
MEIOSIS
Haploid
spores
(n)
MITOSIS
♀
Gametophyte
(multicellular
haploid)
(n)
MITOSIS
Gametes
(n)
Gamete
(n)
Gamete
(n)
MITOSIS
♂
Gametophyte
(n)
FERTILIZATION
Zygote
(2n)
MITOSIS

FIGURE 9-6: Overview of alternation of generations.

- **Gametophyte generation:** Meiosis produces haploid cells called spores (also called *meiospores*).The first cell of the gametophyte generation is the spore. The spores then divide by mitosis to produce a multicellular haploid structure called a *gametophyte* (*gameto* for gametes and *phyte* for plant, so literally a gamete-bearing plant). Cells of the gametophyte generation are haploid. The gametophytes produce gametes by mitosis. Gametes are part of the gametophyte generation, but once they fuse together during fertilization, the sporophyte generation begins.

- **Sporophyte generation:** When gametes fuse together, they create a diploid zygote. The first cell of the sporophyte generation is a zygote. The zygote then divides by mitosis to produce a multicellular diploid structure called a *sporophyte* (*sporo* for spores and *phyte* for plant, so literally a spore-bearing plant). Cells of the sporophyte generation are diploid. Sporophytes produce spores by meiosis, which starts a new life cycle with the gametophyte generation. Scientists call the cell of the sporophyte generation that undergoes meiosis a *spore mother cell* or *meiocyte*.

REMEMBER

Because a complete plant life cycle includes both the gametophyte and the sporophyte generations, scientists refer to the plant life cycle as having an *alternation of generations*. Meiosis causes the change from the sporophyte to the gametophyte generation, whereas fertilization causes the change from the gametophyte to the sporophyte generation.

The balance between the gametophyte and sporophyte generation shifts between different groups of plants. In many of the oldest plant groups, like mosses and liverworts, the gametophyte generation is large and visible. The trend through the evolutionary history of plants, however, is for the gametophyte generation to get smaller and more protected by the sporophyte.

Figure 9-7 shows an example of the life cycle of *Marchantia*, a member of an ancient plant group called liverworts (Chapter 14 presents this group of plants in detail.) In liverworts, the gametophyte generation is dominant. In other words, if you were in a wet place in the woods, maybe near a stream, and saw some of these flat, leafy plants growing on the rocks, what you'd be looking at is haploid gametophyte tissue. The sporophyte generation in liverworts is very small, forming in pockets of tissue on the gametophyte and never living independently.

In ferns, which evolved more recently and are vascular plants, the gametophyte generation is still visible, but the sporophyte generation is dominant. When you see ferns growing in the woods or by the roadside, you're looking at diploid sporophyte tissue. To see a fern gametophyte, you'd have to get down on your hands and knees and look around on the ground under the fern fronds. Fern gametophytes aren't very large — about the size of your thumbnail — and look like little green hearts. Figure 9-8 shows alternation of generations in a fern life cycle. (Chapter 14 goes into ferns in more detail.)

More recent still, in terms of evolutionary age, are the flowering plants. Flowering plants are much more comparable to people in the way they run their life cycle — the main plant is diploid, and the gametophytes are restricted to just a few cells that produce gametes. (Chapter 16 gives you the full scoop on flowering plants).

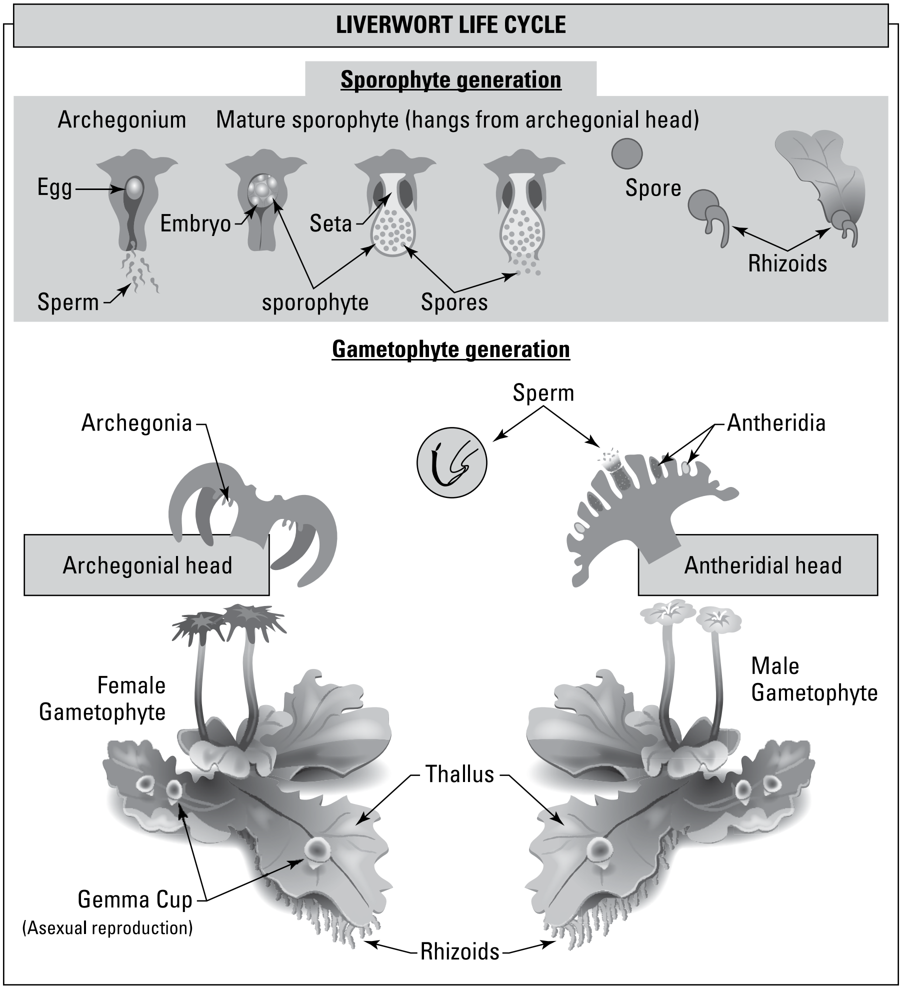

LIVERWORT LIFE CYCLE
Sporophyte generation
Archegonium
Mature sporophyte (hangs from archegonial head)
Egg
Embryo
Seta
Spore
Sperm
sporophyte
Spores
Rhizoids
Gametophyte generation
Sperm
Archegonia
Antheridia
Archegonial head
Antheridial head
Female Gametophyte
Male Gametophyte
Thallus
Gemma Cup
(Asexual reproduction)
Rhizoids

FIGURE 9-7: Alternation of generations with gametophyte dominant (liverwort as example).

In order to understand why gametophytes are so tiny in vascular plants, you have to know a little bit about where plants came from. Life began in the ocean, so the earliest plants were surrounded by water. When some intrepid plants started to creep out onto the land, they had to make a lot of adjustments to get the water they needed and keep from drying out. (See Chapter 11 for some of the amazing ways that plants adapt to different environments.) But the way many plants made life on land work for them was to make changes in their sporophytes, such as developing protective cuticles to retain water and vascular tissue to move water throughout the plants. Instead of changing the gametophytes, these plants evolved mechanisms for protecting them. In the earliest vascular plants, such as ferns, gametophytes are small and short-lived, surviving only in the wet season of the year. In seed plants like gymnosperms (see Chapter 15) and flowering plants (see Chapter 16), the gametophytes can survive in dry conditions because they're totally enclosed in sporophyte tissue.

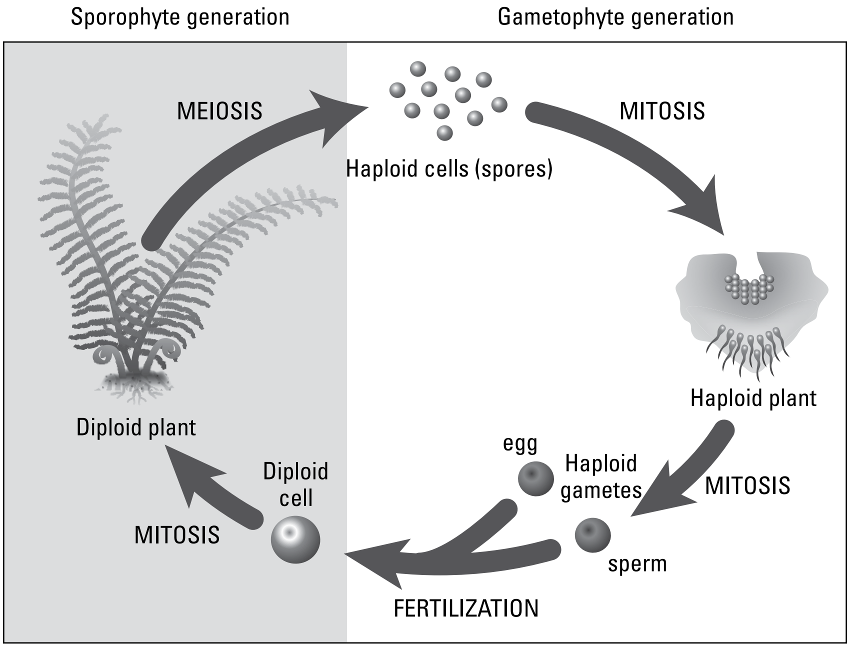

Sporophyte generation
Gametophyte generation
MEIOSIS
Haploid cells (spores)
MITOSIS
Haploid plant
MITOSIS
egg
Haploid gametes
sperm
FERTILIZATION
Diploid cell
MITOSIS
Diploid plant

FIGURE 9-8: Alternation of generations with sporophyte dominant (fern as example).

IN THIS CHAPTER

- Discovering the laws of inheritance with Gregor Mendel
- Digging into monohybrid and dihybrid crosses
- Mastering the lingo of genetics
- Changing plant characteristics via epigenetics

Chapter 10

Passing Plant Characteristics to the Next Generation

Through genetics, scientists and doctors can understand the transmission of genetic diseases, farmers can breed the best crop plants and animals, and everyone can appreciate how their own traits connect to those of their families. Everything scientists know today about genetics began with plants and the breeding experiments of an Austrian monk named Gregor Mendel. This chapter presents the fundamentals of genetics that were originally revealed by Mendel and then takes a look at some modern developments in plant genetics.

Tracking the Inheritance of a Single Gene

REMEMBER

Genetics is the study of inheritance — in other words, tracking traits from one generation to the next. Plant cells contain pieces of DNA, called *chromosomes*, that determine the traits of the organism. A *gene* is a section of a chromosome that contains the code for a worker molecule, such as RNA or proteins, in a cell. (For more on DNA, RNA, and proteins, see Chapter 2.)

Each chromosome within a cell may contain hundreds of individual genes. Cells use their genes as blueprints to build the molecules that determine their structure and function. So, an organism's genes lead to certain molecules that define the traits of the organism. For example, a gene in a flowering plant might contain the information for building an enzyme whose job it is to produce a colored pigment in the flower of the plant. Depending on the code in the genes of a plant, the plant may have purple or white flowers.

TIP

You can think of each set of chromosomes in a cell as a file cabinet. The drawers in the file cabinets represent the chromosomes, and the files in the drawer represent the genes contained on that chromosome. When a cell needs to build a particular worker molecule, it goes to a particular drawer (chromosome) and finds the file (gene) that contains the blueprint for that molecule. The cell then uses the blueprint as instructions for building the molecule.

REMEMBER

Most plant cells are diploid, meaning they have two full sets of chromosomes, so they have two copies of every gene. You can think of a diploid cell as having two complete file cabinets, one copied from Mom's files and one copied from Dad's. The file cabinets contain matching drawers, or chromosomes. In other words, for every drawer in the file cabinet from Mom, a matching drawer in the file cabinet from Dad contains the same kinds of information. If the drawer from Mom contains files (genes) for making molecules that determine flower color, then the drawer from Dad also contains files that determine flower color.

The genes an organism receives from its parents interact with each other to determine the unique characteristics of the offspring. For example, if a flowering plant receives genes that specify purple flowers from both Mom and Dad, then the offspring will have purple flowers. If a flowering plant receives genes that specify white flowers from both Mom and Dad, the offspring will have white flowers. These examples, where the offspring look just like the parents, probably seem pretty simple to you. But what if one parent gives a message for purple flowers and the other parent gives a message for white flowers? To understand the answer to that question, you need to take a look at the work of Gregor Mendel, who did exactly that experiment with purple- and white-flowered pea plants.

Investigating plants with Gregor Mendel

Gregor Mendel was an Augustinian monk who lived in the 1800s, way before anyone knew anything about chromosomes, DNA, genes, or even meiosis. Yet, without knowing anything about the cellular components involved, Mendel was able to figure out the fundamental rules that govern inheritance. Mendel made his great discoveries by spending seven years carefully observing, counting, and analyzing the results of breeding experiments in pea plants. Although many people had done breeding experiments with crop plants and animals before Mendel, one thing that made his work unique was that he carefully applied mathematical analysis to his work. The ideas that Mendel proposed to explain the mathematical patterns he saw in his breeding experiments have withstood the test of time and have become the founding principles of the science of genetics.

Mendel did his work on pea plants in the garden of the abbey where he was a monk. He studied many different traits of pea plants, including flower color, pea shape, pea color, pod shape, and plant height. Peas were very useful for his experiments because pea plants are *self-fertile:* Pea flowers contain both male and female parts and can make offspring after being mated to themselves. If Mendel wanted to ensure that a pea plant didn't reproduce with itself, he snipped the male parts off the flowers.

So, Mendel was able to *outcross* pea plants by mating pea plants to other pea plants and also *self-cross* pea plants by mating them to themselves:

- To do a self-cross, Mendel brushed pollen from a flower onto the female parts of the same flower.
- To do an outcross, Mendel brushed pollen from one plant onto the female parts of a different plant.

After performing a mating, Mendel waited for the plants to produce pea pods (the fruit), containing peas (the seeds). Then he collected the offspring peas and planted them. After the offspring grew, he recorded their traits.

REMEMBER

Before he began his experiments, Mendel used the ability of pea plants to self-cross to create *pure-breeding* lines of plants, plants that always produced the same version of a trait in the offspring between two pure-breeding individuals.

For example, Mendel created pea plants that were pure-breeding for flower color — purple-flowered plants that always produced purple-flowered off spring, and white-flowered plants that always produced white-flowering offspring. He made the pure-breeding plants by self-crossing plants of each color for many generations, always removing any offspring that didn't have the right flower color, until the plants consistently produced only one color flower. By creating pure-breeding plants, Mendel knew he was starting any experiment with plants that gave a certain message to their offspring.

To begin one of his experiments, Mendel chose pure-breeding parents that had different variations of a trait he was interested in and then followed the trait for several generations. To keep track of the generations in a genetic cross, such as the one Mendel performed between purple- and white-flowered peas (see Figure 10-1), scientists use a specific notation:

- **The parental generation is identified as P_1.** P_1 plants are always pure-breeding for the trait that is being studied. For example, to study the inheritance of flower color, Mendel crossed pure-breeding purple-flowered peas with pure-breeding white-flowered peas.

- **The cross between the parentals produces the first generation of offspring, called the F_1 generation.** F stands for filial, which refers to children, so the F_1 generation is the *first filial generation* or the first generation of offspring from the parental cross. Mendel collected the peas produced by his parental cross, planted them, and observed the traits of the offspring. In the case of purple flower crossed with white flower, all the F_1 plants made purple flowers.

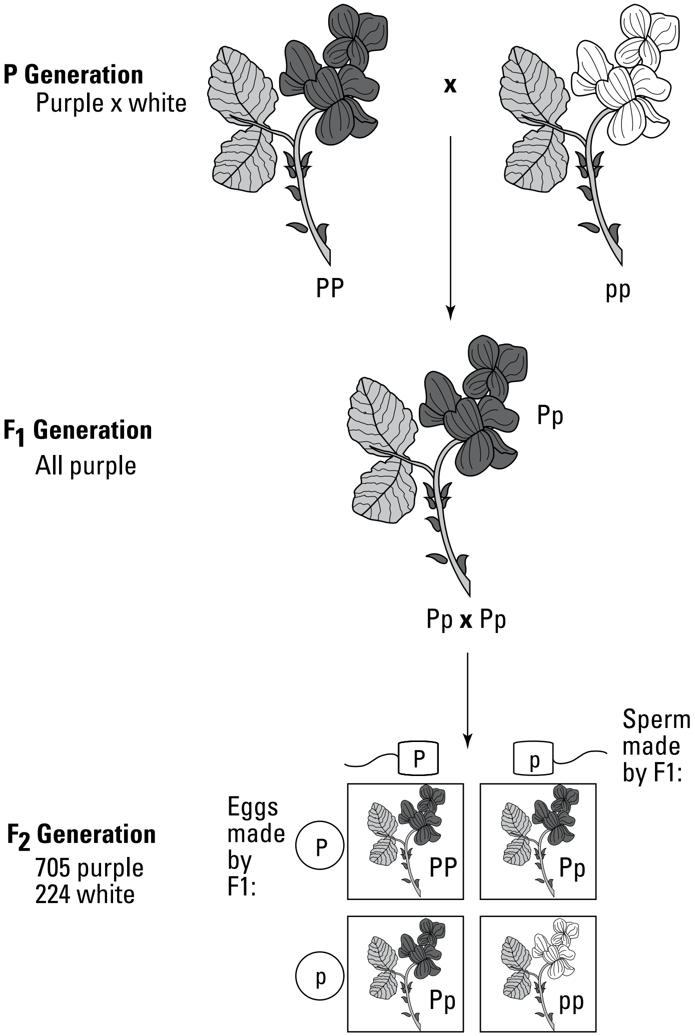

P Generation
Purple x white
x
PP
pp
F_1 Generation
All purple
Pp
Pp x Pp
Sperm made by F1:
P
p
Eggs made by F1:
P
p
F_2 Generation
705 purple
224 white
PP
Pp
Pp
pp

FIGURE 10-1: Mendel's cross between purple- and white-flowered peas.

- **A cross between two members of the F_1 generation produces the second generation of offspring, called the F_2 generation.** F_2 stands for *second filial generation*. Mendel crossed different individuals in the F_1 generation with each other, collected the seeds, planted them, and observed the traits of the F_2 generation, which produced 705 purple- flowered plants and 224 white-flowered plants.

Figuring out the rules of inheritance

Mendel noticed several important things about his crosses that led him to propose some very big ideas that scientists now call *Laws of Inheritance:*

- **The *Law of Unit Characters,* which is also referred to as the idea of *particulate inheritance,* states that each plant has two copies of every gene and that each pair of genes controls the inheritance of various characteristics.** Scientists call the different variations of genes *alleles*. For example, for the gene that controls flower color in peas, each plant may have two alleles for purple color, or it may have two alleles for white color, or it may have one allele for each color.
  - **What Mendel saw:** A variation of a trait, such as white flowers, could disappear in the F_1 generation and reappear in the F_2 generation.
  - **What Mendel concluded:** Each plant must have two factors that control each trait. Even though all the plants in the F_1 generation appear to be the same and only show the effect of one factor, the other factor appears again in the F_2 so it must be present in the F_1.
- ***The Law of Dominance* says that for any pair of alleles, one allele may mask the effect of another.** Scientists describe the observable allele as *dominant* and the hidden allele as *recessive*.
  - **What Mendel saw:** One variation of a trait may hide another variation. For example, plants of the F_1 generation shown in Figure 10-1 must have received a message for purple flowers from one parent and a message for white flowers from the other parent, but they all show purple flowers.
  - **What Mendel concluded:** For each pair of factors that control a trait, one factor may hide the effect of another.
- **The *Law of Segregation* says that each pair of alleles separates during meiosis, so that gametes receive one of each pair.** The *somatic,* or body,

cells of a parent are diploid, but the gametes produced by a haploid gametophyte are haploid.

  - **What Mendel saw:** In the F2 generation, the ratio of plants with the dominant trait to plants with the recessive trait was approximately 3:1. For example, the cross shown in Figure 10-1 produced 705 purple-flowered plants and 224 white-flowered plants, which you can write as a ratio of 705:224. If you divide both numbers by 224 to reduce the ratio, you get a final ratio of 3.15:1. This 3:1 ratio is what you would expect if F_1 parents gave one copy of each message to their F_2 offspring. (See the squares at the bottom of Figure 10-1.)
  - **What Mendel concluded:** Parents have a pair of factors that control each trait, but they pass only one copy of each factor to each offspring.

REMEMBER

Segregation of alleles occurs during meiosis I, when homologous chromosomes separate from each other. (See Chapter 9 for more on meiosis.)

WARNING

Many people have a common — but wrong — idea that dominant alleles are more common in populations. On the surface, this idea seems reasonable — if an allele can hide another allele, it will show up more, right? If the two alleles were present in equal amounts in the population, that assumption would be true, but it isn't necessarily the case. The only way to know whether a trait is dominant or recessive is to look at an individual that has two different alleles for a single trait. The appearance of the trait in that individual tells you whether the trait is dominant or recessive.

Speaking like a geneticist

Since Mendel's day, scientists have learned a lot more about inheritance, and they've developed a whole language and standard symbols of genetics to describe their thinking. In order to understand what scientists are saying and solve problems in genetics, you need to master some fundamental terms:

- **Chromosome, gene, allele, and locus:** I already defined chromosome, gene, and allele in the previous sections, but it's probably still helpful to you if I put them in context relative to one another. Chromosomes contain coding regions (or DNA sequences) called genes. Variations in the code of a gene lead to different alleles of the gene. The place where a particular gene is located on a chromosome is called a *locus.*
  - *Plant geneticists represent different alleles by using letters of the* alphabet — usually the first letter of the trait being studied. For example, a plant geneticist might use the letter P to represent the purple allele for flower color in peas.

  - If a gene has two alleles, plant geneticists use the same letter for both alleles of the trait, but they indicate the dominant allele with a capital letter and the recessive allele with a lowercase letter. So, if the purple allele is P, then the white allele is p (and not w).

- **Wild-type and mutant:** Wild-type is the normal or typical form of a trait found in the majority of individuals of a species in nature. Mutant is anything different from wild-type.
- **Genotype and phenotype:** The alleles an organism has for a particular gene is called its *genotype.* The way the organism appears and functions because of its alleles is its *phenotype.* The genotype is the blueprint for the organism; the phenotype is what is built from that genotype. In Figure 10-1, the genotype for flower color of the F_1 generation is shown as Pp, indicating the alleles for the trait. The phenotype of the F_1 generation is how the plants look for this trait, which is "purple flowers."
- **Homozygous and heterozygous:** Organisms that are homozygous for a gene have two identical alleles. Organisms that are heterozygous have two different alleles. In Figure 10-1, the parentals are both homozygous for flower color (written PP or pp), whereas the F_1 generation is heterozygous (Pp). Organisms with two different alleles are also commonly called *hybrids.* An organism that is heterozygous for one gene is called a *monohybrid*.

REMEMBER

The crosses between individuals in the F1 generation are called *monohybrid crosses* because they are matings between two individuals that are heterozygous, or hybrid, for one trait. *Homo* means *same*, so homozygous is having the same two messages for a gene. Hetero means different, so heterozygous is having two different messages for a gene.

Making predictions

The square shown at the bottom of Figure 10-1 is a *Punnett square*, a tool that geneticists use to diagram and predict the results of a genetic cross. On the edges of a Punnett square, you write symbols for the alleles in the gametes that are combining in the cross. By filling in the square, you create all the possible combinations of gametes that may occur in the next generation.

For example, the Punnett square in Figure 10-1 shows the predicted outcome of a monohybrid cross. Each member of the F_1 generation is heterozygous, having two different alleles for flower color (Pp). When these plants make eggs and sperm, they will give one allele to each gamete (either P or p).

To make the Punnett square for a monohybrid cross:

1. **Use the parents' genotypes to figure out the genotypes for the gametes they produce.**

   Each gamete receives only one allele for each pair of alleles in the diploid parent. A diploid parent that has the genotype Pp will ultimately produce gametes that have either the genotype P or the genotype p.

   In plants, diploid sporophyte parents don't directly make gametes — first, they make haploid spores by meiosis that go on to make gametes by mitosis. Because the gametophytes and the gametes have the same genotype, it's easier to just think about the ultimate products of meiosis being gametes.

2. **Write the genotypes for the gametes from each parent along one side of the Punnett square.**

   Eggs, which can either be P or p, are written along one side of the square; sperm, which can also either be P or p, are written along the other side of the square.

A WONDER OF A WEED

Gregor Mendel worked with peas, but most of today's plant geneticists work with a tiny little mustard plant that could be growing like a weed right now in a field near you. *Arabidopsis thaliana*, sometimes called the mouse-ear cress, has become the lab rat of plant genetics. *A. thaliana* is great for studies in genetics for lots of reasons: It's tiny, so it can be grown easily in labs and greenhouses; it completes its life cycle from seed to seed in about 6 weeks so scientists don't have to wait long to get the results of a cross, and it produces lots and lots of off-spring, as many as 15,000 seeds per plant. And, *A. thaliana* might look like a little weed to you, but to scientists, it still qualifies as a flowering plant. And importantly, it has many of the same genes as other flowering plants, including those that have agricultural interest to people.

A. thaliana is also easy to work with because, as far as plants go, *A. thaliana* doesn't have that many genes, enabling scientists to figure out the sequence of its entire genome — in other words, to read the code of all its 115,409,949 base pairs of DNA and determine that it has a total of about 28,000 genes. By studying the genes of *A. thaliana*, scientists learn about the genes of plants that are valuable to people. Through studies of this little weed, scientists have learned a great deal about the genes that control plant growth, seed production, pest resistance, flowering — you name it, really. Organisms like *A. thaliana* that are studied in labs as a way to know more about life in general are called *model organisms*. And *A. thaliana* is certainly a model that good things can come in small packages.

3. **Write the combinations of alleles that result from each type of egg combining with each type of sperm to create the predicted genotypes for the F_2 generation.**

   If a P egg is fertilized by a P sperm, the result will be an offspring that is PP. If a P egg is fertilized by a p sperm, or if a p egg is fertilized with a P sperm, the result will be offspring that are Pp. If a p egg is fertilized by a p sperm, the offspring will be pp.

   REMEMBER

   The ratio of genotypes predicted in the F2 is 1 PP for every 2 Pp for every 1 pp. In other words, a *genotypic ratio* of 1:2:1. You can also express the proportion of genotypes as fractions: ¼PP, ½Pp, ¼PP.

4. **Use what you know about the relationship between the alleles to figure out the phenotype for each offspring in the F_2 generation.**

   For flower color in peas, the purple allele is dominant to the white allele. (You know this because the original cross between purple and white parentals produced all purple offspring in the F_1.) So, F_2 offspring with the genotype PP or Pp will be purple, whereas F_2 offspring with the genotype pp will be white.

REMEMBER

The ratio of phenotypes predicted in the F2 is 3 purple offspring for every one white offspring — in other words, a *phenotypic ratio* of 3:1. Anytime you see a phenotypic ratio of 3:1, it suggests a monohybrid cross where the relationship between the alleles is simple dominance. You can also express the proportion of phenotypes as fractions: ¾ purple to ¼ white.

Punnett squares represent predictions about the result of a cross. The actual results, recorded from observations of the offspring, may differ from the predictions. For example, the Punnett square in Figure 10-1 predicts a 3:1 phenotypic ratio for plants with purple:white flowers. Mendel's actual data was 705 purple-flowered plants and 224 white-flowered plants, which is a ratio of 705:224 or 3.15:1. The Punnett square predicts outcomes based on a completely even mixing between different gamete types. In real matings, this perfect matching doesn't always occur because each fertilization of one egg and one sperm is a random event. The more offspring produced in a mating, the closer the actual observations will be to the prediction made in a Punnett square.

Tracking the Inheritance of Two Independent Genes

By carefully studying the outcome of a cross involving a single gene, Mendel revealed many of the fundamental principles of genetics. But obviously, peas and other organisms have many, many genes — rice plants, for example, have over

40,000 genes and people have about 22,000. So what does inheritance look like when you consider more than one gene at a time? Obviously, the more genes you try to track at once, the more complicated it gets! But by tracking two genes at once, Mendel discovered another fundamental principle of genetics that applies to the inheritance of multiple genes.

REMEMBER

The *Law of Independent Assortment* says that allele pairs for two or more different genes segregate independently during meiosis and the gametes produced combine randomly.

You can best understand the full meaning of this law and how Mendel discovered it by studying a *dihybrid cross*, a mating between two individuals who are heterozygous for two different traits.

Adding plant height to the mix

One characteristic of pea plants that Mendel studied was plant height. Pea plants may be tall, or dwarf, which is very short. When pure-breeding tall plants are crossed with pure-breeding dwarf plants, the F_1 offspring are all tall, showing that tall is dominant to dwarf. A monohybrid cross between the F_1 results in a 3:1 ratio of tall: dwarf in the F_2 generation, indicating that a pair of alleles controls this trait and that their relationship to each other is one of simple dominance.

To study the inheritance of two traits at once, Mendel crossed parental plants that were pure-breeding for two characteristics. For example, Figure 10-2 shows a cross between tall plants with purple flowers and dwarf plants with white flowers. The F_1 offspring are all tall plants with purple flowers.

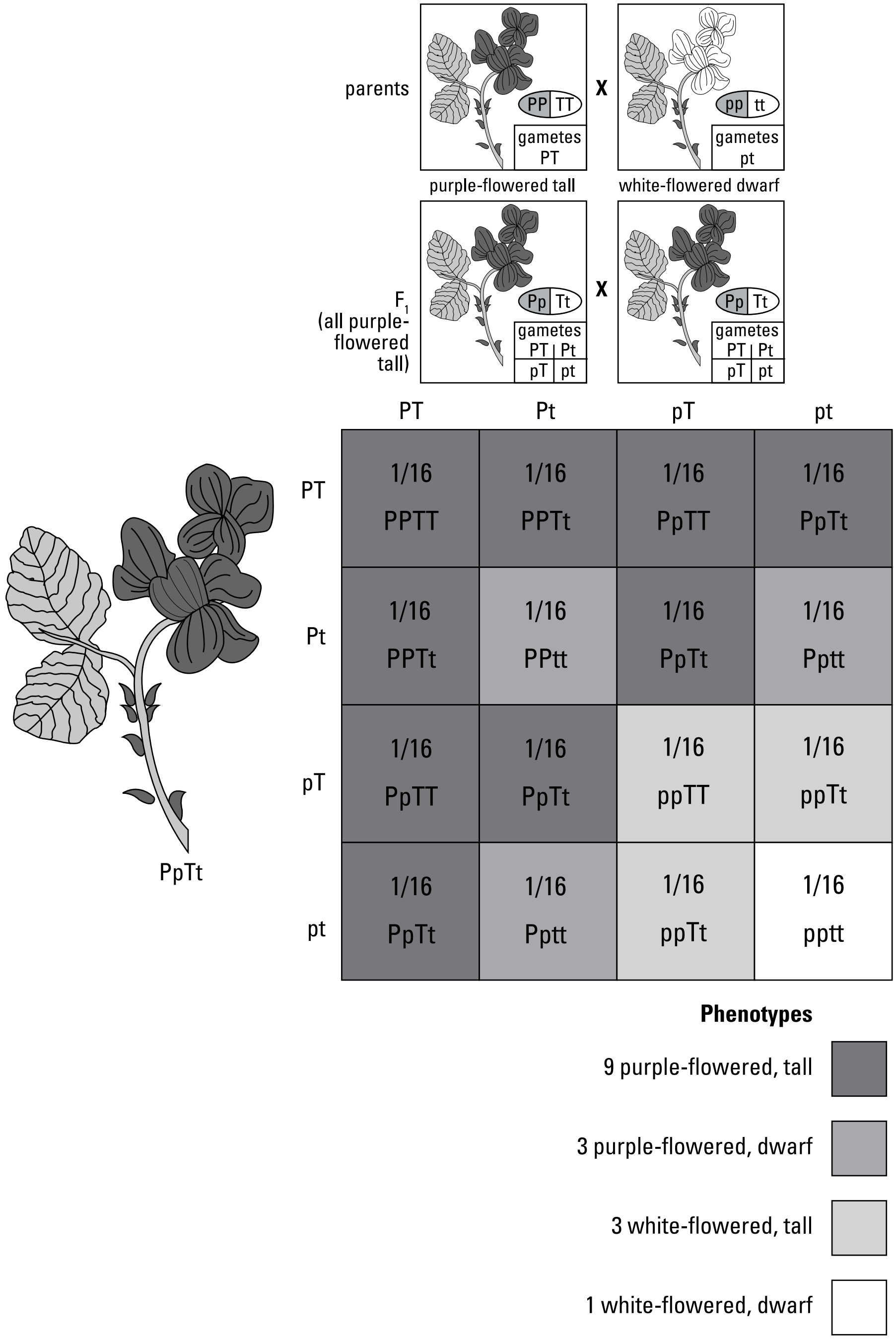
Based on the results in the F1, you can begin to set up the notation for the cross:

1. **Tall is dominant to dwarf and purple is dominant to white.**

   To represent the gene that controls plant height, you can use T for the tall allele and t for the dwarf allele. To represent the gene that controls flower color, you can use P for the purple allele and p for the white allele.

2. **Each plant has two copies of each gene.**

   You can begin to assign genotypes with the P_1 generation. Parents are pure-breeding, so they must be homozygous for both traits. That makes the tall purple parent's genotype PPTT and the dwarf white parent's genotype pptt.


parents
PP TT
gametes
PT
X
pp tt
gametes
pt
purple-flowered tall
white-flowered dwarf
F_1
(all purple-flowered tall)
Pp Tt
gametes
PT | Pt
pT | pt
X
Pp Tt
gametes
PT | Pt
pT | pt
PpTt
Phenotypes
9 purple-flowered, tall ■
3 purple-flowered, dwarf ▩
3 white-flowered, tall ▨
1 white-flowered, dwarf □

	PT	Pt	pT	pt
PT	1/16 PPTT	1/16 PPTt	1/16 PpTT	1/16 PpTt
Pt	1/16 PPTt	1/16 PPtt	1/16 PpTt	1/16 Pptt
pT	1/16 PpTT	1/16 PpTt	1/16 ppTT	1/16 ppTt
pt	1/16 PpTt	1/16 Pptt	1/16 ppTt	1/16 pptt

FIGURE 10-2:
A dihybrid cross.

3. **Parents give one copy of each gene to offspring.**

   Each parent must give one copy of the height gene and one copy of the flower color gene to its offspring. Because the parentals are homozygous, they can give only one type of allele for each gene. Tall purple parents give a tall allele (T) and a purple flower allele (P) to their offspring, whereas dwarf white parents give a dwarf allele (t) and a white flower allele (p). When sperm and eggs combine, they produce the F1 generation, which are all dihybrids (PpTt).

The next step is to figure out what happens when you cross two of the dihybrids from the F1 generation.

Solving the Punnett square for a dihybrid cross

The dihybrid cross follows the same rules as the monohybrid cross: Parents have two copies of each gene, and they must give one copy of each gene to their offspring (by giving one copy of each gene to gametes). What makes the dihybrid cross more challenging is that you have to think about two different genes when you're assigning genotypes to gametes.

Dihybrids are heterozygous for both genes, so they have two possibilities for each gene when you consider which alleles they'll give to gametes. For example, the F1 generation shown in Figure 10-2 are all tall plants with purple flowers that have the genotype PpTt.

Dihybrid plants can make four different types of gametes:

- A gamete with a purple allele and a tall allele (PT)
- A gamete with a purple allele and a dwarf allele (Pt)
- A gamete with a white allele and a tall allele (pT)
- A gamete with a white allele and a dwarf allele (pt)

TIP

Anytime you're doing a cross involving two different genes, you can use FOIL to figure out the gamete types. FOIL stands for first, outer, inner, last. When you look at the two pairs of alleles for two genes (like in a dihybrid that's AaBb), take the first member of each pair (the A and the B), the outside member of each pair (the A and the b), the inside member of each pair (the a and the B), and the last member of each pair (the a and the b). If you remember FOIL, you'll always make sure to get all possible gamete types. In this example, they're AB, Ab, aB, and ab.

Once you've figured out the gametes produced by the dihybrid parents, you set up the Punnett square just as you would for a monohybrid cross:

1. **Write the gamete types produced by each parent along the edges of the Punnett square.**

   Because dihybrids make four types of gametes, the Punnett square will be a 4x4 square, with a total of 16 boxes.

2. **Bring the possible gametes together, writing the combination in the box at the intersection of the two gamete types.**

   The combinations of alleles represent the predicted genotypes for the F_2 generation.

3. **To figure out the genotypic ratio in the F_2., make a list of the different genotypes and count up how many examples you find of each genotype.**

   For the cross shown in Figure 10-2, the possible genotypes are PPTT, PPTt, PPtt, PpTT, PpTt, Pptt, ppTT, ppTt, and pptt. When you count up the examples, you'll find 1 PPTT, 2 PPTt, 1 PPtt, 2 PpTT, 4 PpTt, 2 Pptt, 1 ppTT, 2 ppTt, and 1 pptt.

   The genotypic ratio for a dihybrid cross of two genes with simple dominance is 1:2:1:2:4:2:1:2:1.

REMEMBER

4. **Figure out the phenotypic ratio in the F_2.**

   Using what you know about the relationship between the alleles — in other words, which one's dominant and which one's recessive — figure out the phenotypes that result from each genotype. For the cross in Figure 10-2, the phenotypes from each genotype are purple tall from PPTT, PPTt, PpTT, and PpTt; purple dwarf from PPtt, and Pptt; white tall from ppTT and ppTt; and white dwarf from pptt.

   Then make a list of the different phenotypes and count up how many examples you find of each one. In Figure 10-2, the F2 generation has four different phenotypes: tall plants with purple flowers, tall plants with white flowers, dwarf plants with purple flowers, and dwarf plants with white flowers. When you count up how many plants are predicted for each type, you get 9 tall purple, 3 tall white, 3 dwarf purple, and 1 dwarf white.

REMEMBER

   The phenotypic ratio for a dihybrid cross of two genes with simple dominance is 9:3:3:1.

The Punnett square for a dihybrid cross predicts the types and ratios of off spring that you would see in the F2 generation. Actual observed traits may differ from these predictions. For example, what if you crossed two dihybrid plants and produced only 12 offspring? That's not enough individuals to get ratios close to the predictions, which is why geneticists — and Mendel — need to do many crosses and produce lots of offspring. The more offspring you produce, the more likely it is that the observed ratios will be close to the predicted ratios.

When Mendel did dihybrid crosses, he didn't know about genes and chromosomes. He did the crosses, figured out the ratios, and then used those ratios to build an understanding of what was happening in a dihybrid cross. He figured out that the 9:3:3:1 ratio would result only if the "factors" controlling the two different traits, such as plant height and flower color, worked independently so that dihybrids produced four types of gametes. Since Mendel's time, scientists discovered the process of meiosis and figured out just how cells make gametes. And, by studying meiosis, scientists discovered the cellular events behind Mendel's Law of Independent Assortment.

Remembering meiosis

Independent assortment of genes occurs during meiosis I (see Chapter 9). The genes that control two independent genes are located far enough away from each other that they don't travel together other than during meiosis. For example, the gene for flower color may be on one chromosome, whereas the gene for plant height may be on a different chromosome. When homologous pairs of chromosomes line up during metaphase I, each pair of homologous chromosomes lines up independently from the others.

So, when a dihybrid plant makes the spores that lead eventually to gametes, meiosis can happen two different ways with regard to the two genes being studied, as shown in Figure 10-3:

- **Meiosis in one cell may lead to both dominant alleles lining up on the same side of the cell equator.** Both dominant alleles would travel to the same side of the cell, making gametes with both dominant alleles (for example, "PT"). Likewise, both recessive alleles would travel to the other side of the cell, making gametes with both recessive alleles (for example, "pt").
- **Meiosis in another cell may lead to the dominant allele for one gene on the same side of the cell equator as the recessive allele for the other gene.** One dominant and one recessive allele would travel to each side of the cell, making gametes that have one dominant and one recessive allele (for example, "Pt" and "pT").

REMEMBER

Independent assortment of homologous chromosomes during meiosis I is the reason that dihybrids make four types of spores (that lead to gametes).

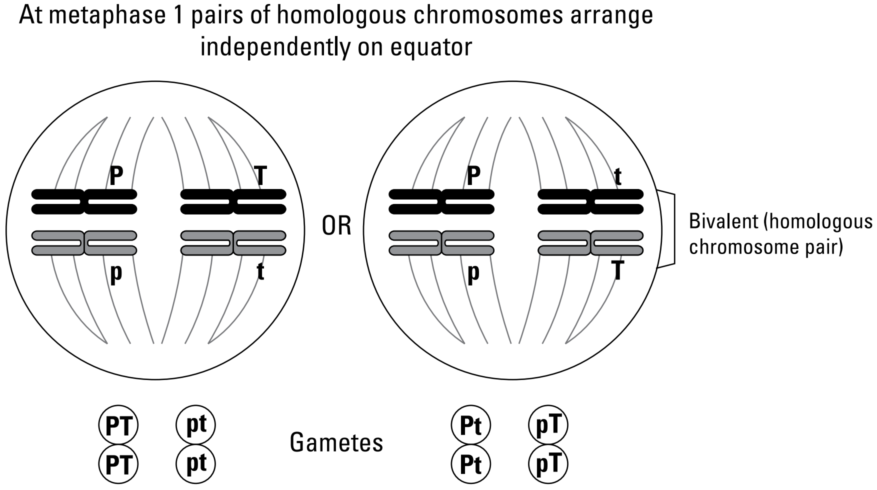

At metaphase 1 pairs of homologous chromosomes arrange independently on equator
P
T
p
t
OR
P
t
p
T
Bivalent (homologous chromosome pair)
PT
PT
pt
pt
Gametes
Pt
Pt
pT
pT

FIGURE 10-3: Independent assortment of homologous chromosomes during meiosis leads to different combinations of alleles in gametes.

Mixing it Up with Incomplete Dominance

Some alleles don't completely hide the effect of other alleles in an organism that's heterozygous for the two alleles. Scientists call alleles that only partially mask the effect of other alleles *incompletely dominant or codominant*. Incomplete dominance results in heterozygotes that have a phenotype halfway between the phenotypes of the two homozygous phenotypes, and codominance results in heterozygotes that have a phenotype that mixes characteristics of the two homozygotes. (They're essentially the same thing on a molecular level.)

In snapdragons, for example, inheritance of flower color can have a different pattern than you've seen in peas:

- **The allele for red color is incompletely dominant over the allele for white color.** Because the relationship between these two alleles is not simple dominance, scientists sometimes use a different type of notation, like the one shown in Figure 10-4. One letter is used to represent both alleles, but the variation between the alleles is represented by a superscripted letter:
  - The allele for red color can be represented as C^R, where C stands for color and the "R" indicates red.
  - The allele for white color can be represented as C^W, where W indicates the white allele.

- **Heterozygotes show a phenotype that looks like a blend of the two alleles.** Snapdragons that are homozygous for the red allele (C^RC^R) have red flowers. Snapdragons that are homozygous for the white allele (C^WC^W) have white flowers. Snapdragons that are heterozygous (C^RC^W) have pink flowers.

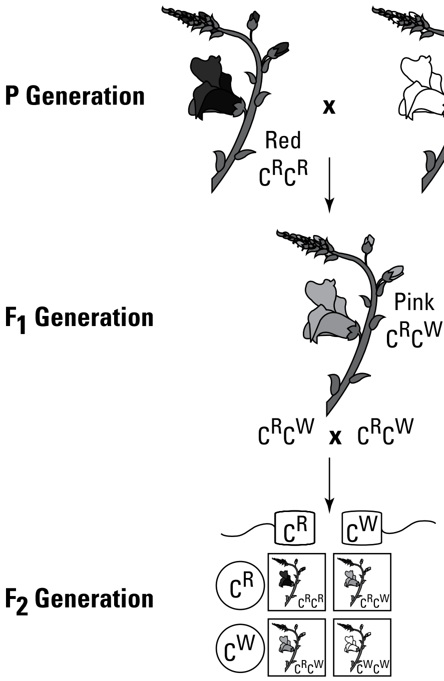


FIGURE 10-4: A Punnett square for incomplete dominance.

Incomplete dominance leads to different phenotypic ratios in genetic crosses than those caused by simple dominance. As an example, Figure 10-4 presents a cross between snapdragons that have red and white flowers:

1. **When red parentals are crossed with white parentals, all the plants in the monohybrid F_1 generation appear pink.**
2. **A monohybrid cross between individuals within the F_1 generation leads to three possible phenotypes and three possible genotypes in the F_2 generation.**

The predicted phenotypic ratio is 1 plant with red flowers: two plants with pink flowers: 1 plant with white flowers, or 1:2:1.

The predicted genotypic ratio is 1 homozygote for red flowers (C^RC^R): 2 heterozygotes (C^RC^W): 1 homozygote for white flowers (C^WC^W), or 1:2:1.

REMEMBER

A monohybrid cross with alleles that are incompletely dominant yields a phenotypic ratio of 1:2:1, which is the same as the genotypic ratio.

Inheriting Traits through Epigentics

Gregor Mendel opened the door to our understanding of how parents pass traits onto their offspring. Since his work, many other scientists added pieces to the puzzle by discoveries like how the process of meiosis separates chromosomes (reviewed in Chapter 9) and how the chemical building blocks in DNA spell out the instructions for RNA and proteins that determine traits (reviewed in Chapter 2). Botanists figured out many aspects of plant growth and development by observing the effect of outright changes in the DNA code of plants (a change in DNA sequence is called a *mutation;* see Chapter 11 for the importance of mutation in evolution).

One of the most recent and exciting developments in plant genetics is the discovery that plant characteristics can change, and can even be inherited from one generation to the next, without mutations in the DNA code.

REMEMBER

Epigenetics is the study of heritable changes from generation to the next that don't involve changes to the actual code of the DNA.

Epigenetic changes in plants (and other organisms) occur when environmental signals affect the ability of cells to use particular genes, rather than causing changes in the genes themselves. Cells attach small chemical groups either to the DNA itself or to the histone proteins around which DNA is coiled to form chromosomes. Depending upon the type of chemical group and where it is attached, the cell may have increased or decreased access to a gene.

TIP

If chromosomes are drawers in a file cabinet and genes are individual files in the drawer, then epigenetic tags might be staples used to temporarily prevent access to a file.

As an example of how epigenetics could work, imagine that a plant has the gene to produce purple pigment in its flowers. If the plant was exposed to a particular environmental condition, chemical tags might attach to some of the bases in the gene, making it impossible for the cell to read the gene and produce the purple pigment. Even though the plant actually has the gene with the correct instructions for producing purple pigment, the flowers of the plant will appear white because the genes are essentially locked.

One of the most amazing discoveries about epigenetics is that a parent can pass its pattern of epigenetic markers to offspring. In other words, a plant that had its purple pigment production turned off could produce offspring that also produced white flowers. This means that some traits in offspring may be affected by the experiences of the parent. To give you some human context that demonstrates how important this is, people who pass through trauma like starvation, alcoholism, and war may develop certain patterns of epigenetic markers that they then pass on to their children. The possible implications of this for human health are currently being investigated.

In plants, epigenetics provides a way for individuals and their offspring to fine tune their traits to a given environment and to cope with environmental change. As an example, epigenetic regulation helps plants optimize their responses to regular changes such as seasonal fluctuations in temperature. The timing of flowering in many plants is affected by the cold period a seed experiences before germination. Scientists studying this phenomenon in *Arabidopsis thaliana* found that exposure to cold caused increased epigenetic marking of the gene for a protein that inhibits flowering. So, the longer the seeds were exposed to the cold, the greater the number of cells that added epigenetic marks to block access to the inhibitor gene. The longer the cold, the more cells that turned off the inhibitor, and the sooner the plants flowered after they began to grow.

One of the really interesting things about epigenetic changes like these is that they remain in place even after the environmental stimulus is gone. In my example above, after the weather warms up, the epigenetic markers don’t disappear. They remain in place and determine the timing of flowering as if the plant remembers that it passed through the cold season.

Humans have been modifying the traits of plants ever since we started farming about 12,000 years ago (for more on the origins of farming see Chapter 19). Traditional modification involves selecting plants with desired characteristics and breeding them together. This can be a slow process. More recently, scientists have developed many tools that allow them to use genetic engineering to rapidly modify the genes of organisms, including important plant species. The discovery of epigenetics opens the possibility for more ways to rapidly change crop plants. Scientists are hard at work figuring out how to trigger epigenetic changes in plant cells and hope to develop methods of using epigenetics to make improvements in flavor or yield of crop plants. One of the remaining issues to be investigated is how stable epigenetic changes are; in other words, to determine the number of generations that epigenetic tags will remain in place.

IN THIS CHAPTER

- » Understanding the sources of genetic change
- » Examining plant evolution
- » Checking out plant adaptations

Chapter 11

Changing with the Times: Evolution and Adaptation

Life on Earth is constantly changing in response to environmental conditions. Life, including plants, migrated from the oceans to the land, dinosaurs have come and gone, and modern humans evolved and spread over the face of the Earth. Biological evolution is the process that leads to changes in the species of life on Earth. Biological evolution occurs through a combination of genetic changes and natural selection. This chapter presents the fundamentals of biological evolution and shows how plant evolution has led to some truly amazing plants.

Figuring Out the Fundamentals of Evolution

Evolution is change that occurs over time. *Biological evolution* more specifically refers to changes in living organisms that occur over time. Life on Earth is constantly changing, usually in ways so small you'd hardly even notice. But if you look over huge spans of geological time — millions or billions of years — you can see the big changes that result from biological evolution, from the migration of life from the ocean to the land to the rise and fall of the dinosaurs. During this history of life on Earth, plants have changed from strictly aquatic organisms to simple land plants that reproduced by spores to the more dramatic cone-bearing and flowering plants that grow all around you today.

Mutation

Evolution is possible because living things have a built-in engine for change. Whenever cells copy their DNA so they can reproduce, the enzyme that copies their DNA makes a few small mistakes called mutations. Scientists call the mutations that normally occur during the copying of DNA *spontaneous mutations*.

Most mutations either have no effect or have a negative impact on the organism. Some mutations lead to significant problems, such as genetic diseases in people. But rarely, a mutation causes a difference that is not negative and may even give an organism an advantage. When you consider the evolution's long timespan, even rare events become possible.

Some environmental factors, such as certain chemicals or types of radiation, can increase the rate at which mutations occur in a cell. Scientists call mutations that are caused by exposure to something outside the cell *induced mutations.* The environmental agents that cause mutations are *mutagens.*

Scientists may use mutagens to deliberately induce mutations in organisms that they're studying. For example, scientists create mutations in the mustard weed *Arabidopsis thaliana,* study the mutant plants in order to figure out which genes are mutated, and then discover the normal function of those genes. *A. thaliana* is a flowering plant that has many genes in common with other flowering plants, so by figuring out how *A. thaliana* functions, scientists also learn something about plants that have economic importance to humans. These discoveries can lead to improvements in yield and pest resistance in crop plants.

Natural selection

Mutations cause changes in individuals or their offspring, but evolution changes in populations over time. In order for changes in populations to occur, other factors must influence the relative success of individuals within the population.

REMEMBER

Natural selection is the theory that, in any given generation, some individuals are more likely to survive and reproduce than others due to their genetic traits. People often refer to this theory as "survival of the fittest." Basically, natural selection means that individuals that have the most advantageous traits in any given circumstance are more likely to survive and reproduce, passing their traits onto their offspring. So, genetic traits that give an advantage will tend to increase in a population, causing that population to change over time.

REMEMBER

The characteristics of organisms that make them suited to their environment are *adaptations*.

Observing the natural world with Charles Darwin

Natural selection was first proposed by Charles Darwin, an English naturalist who made detailed observations both at home and on his travels around the world. Darwin made several observations that led him to propose his idea of *descent with modification* — in other words, living things descend from their ancestors, but the characteristics of groups of descendants can change over time. Darwin saw examples of the impact of evolution all around him in the natural world:

- ***Artificial selection* occurs when people use selective breeding to change populations of farm animals, dogs, crop plants, and other species to change over time.** Darwin observed how farmers, dog breeders, and pigeon fanciers made careful decisions about which individuals to breed in order to influence the traits of the next generation. When he was working out his theory of natural selection, he made many notes about his observations of the changes in domesticated animals and plants.
- ***Extinction* occurs when all members of a particular species die out.** Along a riverbed in Argentina, Darwin discovered the fossil bones of three extinct animal species. The extinct species resembled three living species, so Darwin began to wonder whether the prior species were ancestors to current species and whether all existing species were somehow connected to species in the past.
- ***Adaptive radiation* happens when members of one species become specialists for different types of environments, causing groups of specialists to become new species over time.** Darwin observed adaptive radiation when he traveled to the Galapagos Islands, an island chain off the coast of South America. Darwin particularly focused on a type of bird, called finches, that lived on the Galapagos Islands. Each island had its own unique species of finch that were distinct from each other and from the finches on the mainland. In South America, this type of finch ate only seeds. On the islands,

some finches ate seeds, others ate insects, some even ate cacti. The beak of each type of finch seemed exactly suited to its food source. Darwin thought that all the finches had a common ancestor from mainland South America that either flew or floated to the newly formed islands, perhaps during occasional storms. After the ancestral finches reached the islands and began reproducing, different groups became specialists on unique types of foods. Darwin thought that within each group, the finches that had the beaks that were best able to use that particular food would be more likely to reproduce and pass their type of beak onto offspring. Over long periods of time, the beaks of different groups of finches became distinct from each other.

REMEMBER

When a population becomes so distinct in its characteristics that it can no longer successfully mate with related populations, it is a new *species*. When new species are created, the process is called *speciation*.

Putting the theory together

Before he finally published them, Darwin thought about his ideas on evolution for more than 20 years, partially because he was worried about the reaction of the church to his ideas. During that time, Darwin worked on his ideas, gathering evidence from agriculture, geology, and the natural world to support his thinking. Finally, when Darwin heard that another scientist, named Alfred R. Wallace, was about to publish similar ideas, Darwin felt compelled to share his work with the world.

In his book *On the Origin of Species by Means of Natural Selection*, Darwin presents the fundamental requirements for natural selection to occur:

- **Individuals in most natural populations produce more offspring than can survive.** A single maple tree produces thousands of maple seeds each year, very few of which survive to grow into new maple trees. Each seed must compete with the others for space, light, water, and nutrients.
- **Individuals have unique characteristics.** During Darwin's time, no one knew where these differences came from. Now scientists know that differences in organisms arise due to mutations in DNA and the mixing of genetic information that occurs during sexual reproduction.
- **Some characteristics are inherited from parents to offspring.** During Darwin's time, the laws of inheritance were just beginning to be figured out, so Darwin didn't know exactly how parents passed on their traits. Now scientists know that traits are inherited when parents pass genes onto their offspring. (For more on inheritance, see Chapter 11.)

- **Organisms with characteristics best suited to their environment are more likely to survive and reproduce.** This idea is the heart of natural selection: If organisms must compete to survive and all organisms aren't the same, then the ones with the advantageous traits are more likely to survive — the fastest growing maple seed perhaps. If these traits can be inherited, then the next generation will show more of these advantageous traits. An example of natural selection is shown in Figure 11-1, where a hawk is shown looking for mice to eat. Hawks are visual predators, so they are more likely to attack the mice that are easiest to see. In the figure, light-colored mice shown up better against the background of grass and dirt, so the hawk is more likely to eat them. Over time, the population of mice that lives in this environment is likely to have more darker colored individuals that result from the reproduction of dark-colored survivors. Predation like this can also influence the evolution of plant populations. A browsing herbivore may enjoy eating the individuals of a particular plant species. If some of the individuals in the population had rougher, almost spiny edges on their leaves, the herbivore might avoid these individuals and graze on the softer members of the population. The spiny-edged individuals would survive in greater numbers, producing offspring that also had spiny edges. Over time, the entire population of this plant species might become spiny-edged.

REMEMBER

The environmental factor that causes some organisms to survive and others to not survive is called a *selection pressure*. (Because it puts "pressure" or stress on the individuals of the population.)

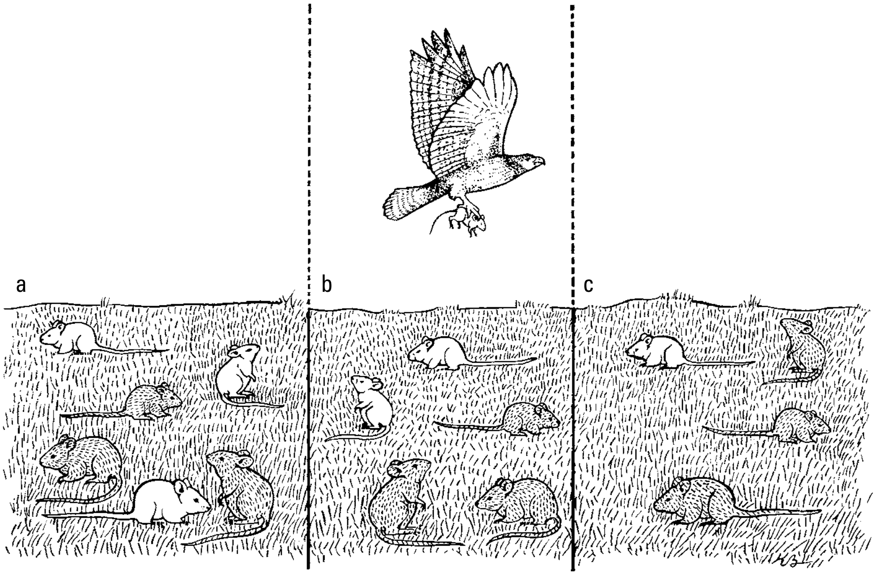


FIGURE 11-1: Natural selection.

WARNING

It's very important to realize that biological evolution happens to populations, not to individuals. Individuals live or die, reproduce or don't, depending on their circumstances. But individuals themselves can't evolve in response to a selection pressure. Imagine a plant growing in the forest under some trees so that it doesn't get quite enough light. The individual plant can't suddenly change itself into a vine that can climb up a tree trunk to get to the light in the forest canopy. But if an individual has a mutation so that some of its leaves are like tendrils that can wrap around things, maybe that individual will be able to maneuver itself into a lighter spot. If some of its offspring have leaves that are even more tendril-like, they may become more successful. Over long periods of geologic time, where natural selection favors the individuals with tendril like leaves, the plant population may evolve into climbing vines.

Moving onto the Land

Evolution made it possible for plants and other organisms to move from the oceans to the land. The closest living relatives of land plants are green algae called charophytes (discussed further in Chapter 13). The earliest plant fossils suggest that plants moved onto the land between 490 and 443 million years ago (during the Ordovician Period). Botanists think that the transition from life in water to life on land probably occurred in shallow ponds and marshes, where aquatic plants had access to water but also experienced higher levels of light. Plants that had characteristics that enabled them to move higher onto the land would benefit from the lack of competition for resources and could produce more offspring than the plants that had to stay totally submerged. Over long periods of time, a population of plants evolved to have features enabling it to survive on land.

The adaptations that enable plants to survive on land include both vegetative and reproductive adaptations:

- Vegetative adaptions include
  - Vascular tissue to transport water throughout the plant
  - A waxy cuticle that prevents plant tissues from drying out, but that contains stomates so that plants can still exchange gases with the atmosphere
  - Formation of a symbiotic association with soil fungi (mycorrhizae) that helped land plants acquire water and minerals from the soil
  - Protective pigments that help block ultraviolet radiation

- Reproductive adaptations include
  - Thick spore walls to protect reproductive spores from drying out
  - Tissues called gametangia that surround and protect gametes (eggs and sperm) from drying out
  - Embryos protected by maternal tissues

The first plants that colonized the land probably had all of these characteristics and were very similar to plants called bryophytes and seedless vascular plants (presented in Chapter 14) that are alive today. The brand-new land environment offered wide open spaces but also had the challenges of increased light and decreased water. These strong selection pressures continued to shape the evolution of land plants, giving rise to new plant groups such as the cone-bearing plants (called gymnosperms, see Chapter 15) and the flowering plants (the angiosperms, see Chapter 16).

Identifying Important Factors in Plant Evolution

Many of the processes that drive evolution, such as mutation, natural selection, migration, and genetic drift, can occur in populations of all types of organisms. But, for each type of organism, certain processes may have greater impacts than others. Plants, for example, don't migrate as easily as animals. Animals, on the other hand, aren't as likely to produce fertile *hybrids*, individuals that are the offspring of two different species (or varieties), as are plants.

You're probably familiar with the example of a horse and a donkey mating to produce a mule. Mules function normally, but can't produce offspring of their own, so they represent an evolutionary dead end. Many plant species, on the other hand, can mate with other species and produce hybrids that are capable of reproducing, potentially leading to new species. Several processes, including hybridization, have made significant contributions to plant evolution.

Hybridization

Most plant hybridization has probably been manmade as a result of human agriculture. As farmers seek to develop crop plants with the most desirable features, they often mate two different varieties of a plant, or even two entirely different species, in order to try and capture certain qualities from each.

TAMING THE WILD GRASSES

A major cultural shift in the human population occurred about 12,000 years ago when people switched from hunting and gathering to farming. Wheat, which is a grass, was one of the first plants to be domesticated. Studies of chromosome number in wild and cultivated varieties of wheat have pieced together the probable evolution of modern wheat varieties. One of the first wild wheat species to be cultivated widely was *Triticum monococcum*, a wheat species with 14 chromosomes (7 homologous chromosome pairs). Emmer wheat, *T. turgidum,* was another very early cultivar and was also gathered by humans of the Paleolithic period (or Stone Age). *T. turgidum* has 28 chromosomes (14 pairs) and probably evolved through gene doubling from *T. monococcum* or a related hybrid.

REMEMBER

When different varieties or species of plants are mated to each other, the F_1 generation is often bigger and healthier than either parent plant. Scientists call the improved health of hybrids *hybrid vigor*.

Most of the species of wheat and corn that farmers grow today are hybrid varieties.

Polyploidy

REMEMBER

About half of all flowering plant species are polyploid, which means they have more than two complete sets of chromosomes. Two different processes seem to have caused polyploid species during plant evolution:

- **Gene doubling by failure of chromosomes to separate during meiosis.** During meiosis, the chromosome number of a cell is supposed to be cut in half in order to produce gametes. *Nondisjunction* is the failure of chromosomes to separate properly during cell division. If nondisjunction occurs, then gametes may be produced that have twice the normal number of chromosomes. If these gametes go on to fertilize other gametes, they can produce polyploid plants.
- **Hybridization followed by gene doubling.** Hybridization may produce hybrids with mismatched sets of chromosomes. These hybrids can't reproduce because they can't successfully complete meiosis. But if a cell of one of these infertile hybrids tries to divide but then fails to separate the chromosomes, it could produce a cell with two complete sets of the originally mismatched chromosomes — in other words, a cell with two matching sets of chromosomes! This cell can now undergo a normal meiosis, producing gametes that can lead to new offspring. (Hybridization and gene doubling appear to have led to the evolution of modern wheat; see the sidebar "Taming the wild grasses" for details.)

Reproductive isolation

Reproductive isolation, which is the separation of two populations so that they can't interbreed, can occur in many different types of organisms. Reproductive isolation can occur because of physical barriers, such as the physical distance between islands in a chain, or because of behavioral barriers such as individuals searching for food at different times or settling in different environments. When two populations become reproductively isolated, they can't mix their alleles anymore, and they may begin to evolve independently from each other. Eventually, they may become so different that they can no longer interbreed and have become distinct species from each other. Scientists call the process *divergent evolution*.

THE SILVERSWORD ALLIANCE

The Haleakela silversword (*Argyroxiphium sandwicense var. macrocephalum*) only grows in one place on Earth, high on the rocky, volcanic slopes of Haleakela, Maui, in the Hawaiian island chain. For most of their lives, these plants grow as spiky spheres formed by curving sword-like leaves that are covered in silvery hairs. The leaves, which are thicker at the base but sharply pointed at the tips, can store water, which helps the silversword survive in their dry alpine environment. After growing for anywhere from 15 to 50 years, individuals put everything they've got into reproduction, sending up a stalk of flowers several times their height, sometimes growing as tall as 10 feet into the air. After this glorious outburst, the plant dies, leaving behind just a dry husk of its former self.

Botanists studying plants in the Hawaiian islands knew that the Haleakela silverswords were related to other plants growing in the islands because of similarities between their leaves and flowers. The plants were also extremely diverse; however, growing in many different environments on the islands as vines and shrubs. This diversity made it difficult for botanists to figure out the exact relationships between the plants, so they put all 30 species together in a group they called *The Silversword Alliance*. Then, genetic studies in the 1980s and 90s allowed botanists to sort out the silversword family tree and helped them figure out how these plants first came to the islands. It turns out that, about five million years ago, a small daisy-like plant (related to plants called tarweeds in the family Asteraceae) arrived on the Hawaiian islands, possibly as a few sticky little fruits hitchhiking on a bird. As these plants grew and reproduced, their descendants spread to many different environments on Hawaii, from the dry mountain heights of Haleakela to lush tropical rainforests. The descendants of the tarweed didn't mix genes with their ancestors on the mainland anymore, and the ones that lived in different environments didn't really mix with each other either. Each population began to diverge from the other, leading to the diversity of species that represent this group today. From their appearances, you would never know they are related to the tarweed that grows on the west coast of N. America. Reproductive isolation on the islands and colonization of diverse environments led to the adaptive radiation of the 30 species in the silversword alliance.

Admiring Plant Adaptations

Some of the truly unique results of plant evolution are the ways in which plants have become specialized to survive and take advantage of the conditions in extreme habitats. When you consider all the amazing strategies plants have evolved for survival, it seems like there's almost no challenge they can't overcome. As examples of the incredible power of plant evolution to create diversity, some very cool plants have evolved to meet the challenges of unique environments.

Desert plants

Life in the desert can be difficult for a plant — deserts are dry, have extremes of temperature (hot during the day, but cold at night), and can have almost too much sunlight. These conditions put strong selection pressures on plants that have strategies to live with low water and protect themselves from dry air and bright light. Many different species of plants live in the desert, but even unrelated species have evolved similar strategies for dealing with desert conditions. Sometimes, two plants that look very much alike because they've adopted the same strategies are completely unrelated to each other.

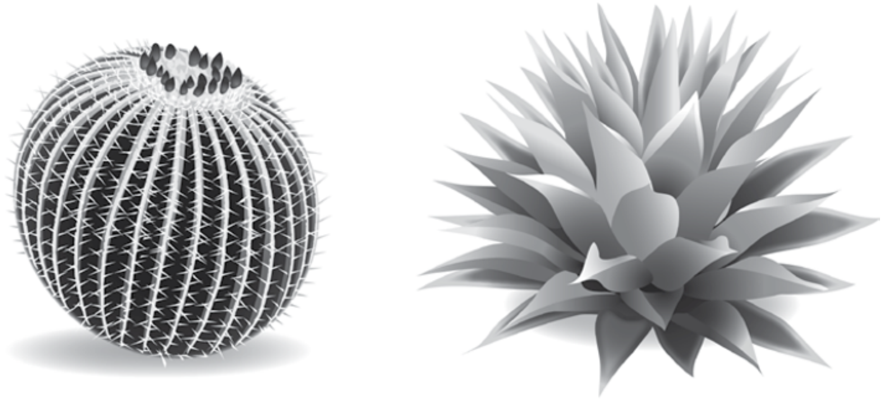
REMEMBER

When two genetically unrelated species evolve to look similar because of similar selection pressures, scientists call the process *convergent evolution*.

Figure 11-2 shows some common strategies plants use to survive desert conditions:

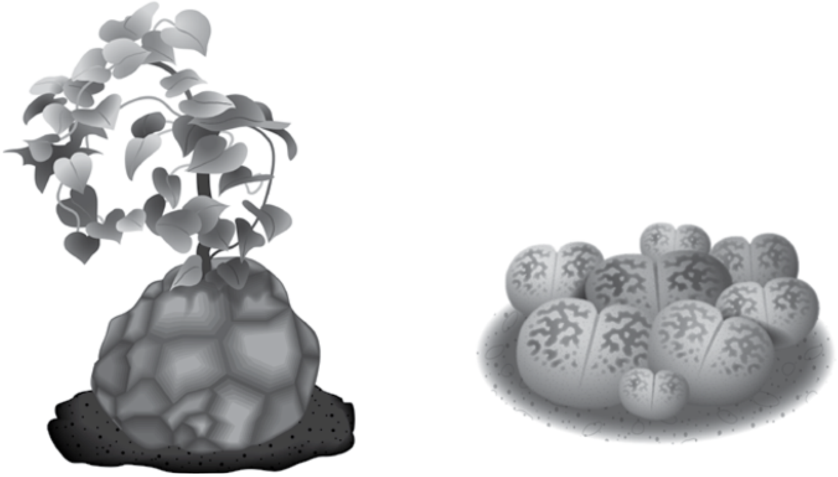
- **Reduced or highly modified leaves:** Many plant leaves are thin and flat, ideal for catching sunlight, but not at all suitable for desert life. Those thin flat surfaces would be exposed to lots of dry air, causing water to evaporate rapidly out of the stomates.
  - In many desert plants, such as the barrel cactus in Figure 11-2, leaves have evolved into spines, which don't lose water rapidly and which protect the plant from grazers. These plants have switched the main site of photosynthesis to the stem.
  - Other desert plants, such as the agave shown in Figure 11-2, have evolved tough, thick leaves that have a heavy wax coating to prevent water loss.
  - Some plants, such as the desert yam shown in Figure 11-2, produce delicate, thin leaves, but they only make them during the rainy season when it's safe! The rest of the year, the leaves die back and only the plants' tough, protective base remains.
- **Organs for water gathering and storage:** Many desert plants are *succulents,* plants that store water in fleshy tissue. All four desert plants shown in Figure 11-2 have ways of dealing with the desert water shortage. Cacti store water in their

stems, which have pleats to allow expansion when water is available. Agave plants have long root systems that can find water under the desert ground. The desert yam stores water in its tough base, and stone plants have succulent stems.



a. Spiny leaves and succulent, photosynthetic stems (barrel cactus)

b. Succulent leaves (agave)



c. Seasonal leaf production (desert yam)

d. Reduced exposure to light (stone plants)

FIGURE 11-2: Common strategies plants use to survive desert conditions.

- **Protection from overexposure:** Too much light or exposure to dry air can damage a plant, so desert plants have evolved structures and strategies to protect themselves from these conditions. Some cacti have very long, white, almost hairlike spines that form a surface barrier over the stem, slowing down air movement and reducing damage from overexposure. Because the spines are white, they also help reflect excess sunlight off the stem. Some plants, such as the stone plant shown in Figure 11-2, snuggle themselves down into the desert floor, allowing just their surfaces to come into contact with the elements. The surface of stone plants have little clear spots that allow sunlight to enter the plant, as if it were passing through a window so that photosynthesis can occur inside the submerged stem.

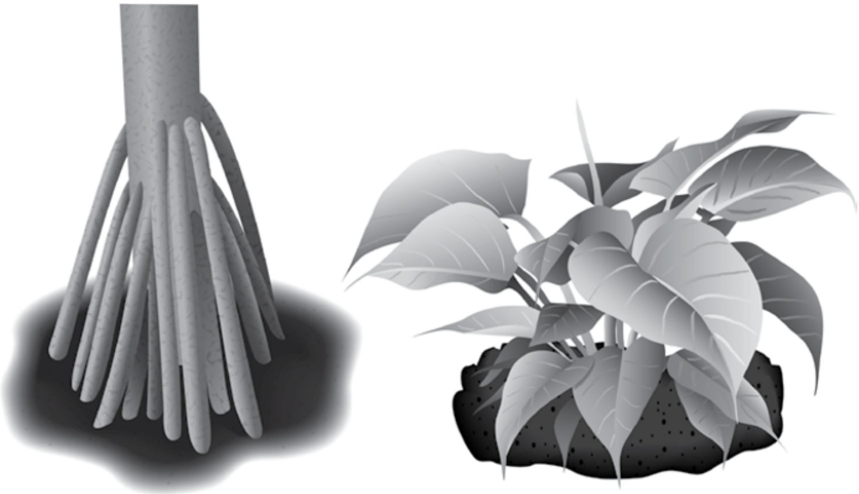
Tropical rainforest plants

The environment of a tropical rainforest is almost the opposite of that of a desert — tropical rainforests are wet, and plants can have a hard time getting enough light. Light is a problem for many plants because the trees of the tropical rainforest spread their big leaves to form a canopy and block light from reaching the plants down below. Another environmental stress in the tropical rainforest is that the soil is not very deep and of poor quality.

These selection pressures caused populations of rainforest plants to evolve unique features that help them succeed in their environment:

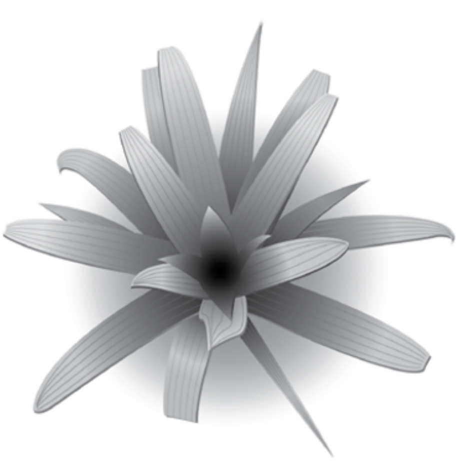
- **Prop, stilt, and buttress roots:** Rainforest soil is so shallow that rainforest trees can't put down deep enough roots to anchor themselves properly. So, many rainforest trees make adventitious roots that help provide additional support. (For more on plant roots, check out Chapter 3.) The prop roots shown in Figure 11-3 are one example of adventitious roots made by rainforest trees.
- **Waxy leaves with drip tips:** Too much water can actually be a problem in the rainforest — if water sits on a plant leaf, the leaf could get heavy and break, or pathogens such as fungi might begin to grow and attack the leaf. So, many rainforest plants have extra wax and a pointed tip on the leaf that help the excess water slide off.
- **Structures for clasping and climbing:** Because of the big leaves on the rainforest trees, the only place in the rainforest that gets lots of light is the upper canopy. The rainforest is full of different kinds of plants that have evolved ways to grow where the action is:
  - *Vines*, such as the liana shown in Figure 11-3, put roots into the soil, but then wrap around other plants in order to grow upward toward the light.
  - *Epiphytes* are plants that grow entirely on other plants, without putting roots into the soil at all. Many tropical orchids are epiphytes, as are the bromeliads like the one shown in Figure 11-3. Because epiphytes have no roots in the ground, they have strategies for getting water and minerals up in the canopy.

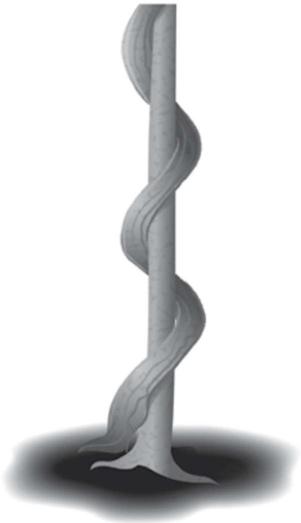
Orchids have adventitious roots covered with spongy material that helps them collect water and particles from the air. Bromeliads are also called tank plants because they form a central water storage area by wrapping their leaves tightly into a cylinder — basically forming a little pond in the center of the plant. Up in the rainforest canopy, tank plants not only catch water for themselves, but they also form homes for little animals, such as tree frogs.



a. Prop roots

b. Waxy leaves and drip tips (philodendron)





c. Epiphytes (Bromeliad)

d. Vines (liana)

FIGURE 11-3: Adaptations of rainforest plants.

Carnivorous plants

Carnivorous plants are the creepy cool kids of the plant world due to their habit of "eating" bugs. These plants grow in many different environments that all have one thing in common: low nutrient availability. Many carnivorous plants grow in acidic environments, such as peat bogs, where the high acid content makes it difficult for plants to take up minerals through their roots. Some carnivorous plants grow as epiphytes in the canopy of tropical rainforests, and so don't put roots into the soil at all. Whatever the reason for the shortage of minerals, carnivorous plants evolved the same solution — catch bugs and absorb the minerals from their rotting corpses!

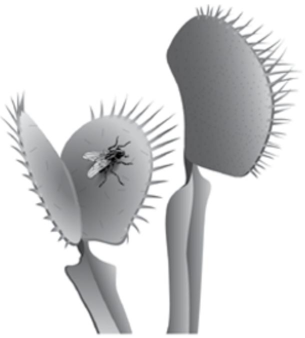
REMEMBER

Carnivorous plants photosynthesize just like all other plants and can make their own sugars from carbon dioxide and water. Thus, they don't need to capture prey to supply themselves with energy or with carbon, hydrogen, or oxygen — they capture prey to supply themselves with minerals, such as nitrogen and phosphorous that they are unable to get from the soil.

Carnivorous plants have evolved many different strategies for catching their prey, including

- **Modified leaves that snap closed to trap prey:** The Venus flytrap, shown in Figure 11-4, is probably the most famous of all carnivorous plants. Its traps are modified leaves, which are covered with hairs that act as triggers to spring the trap. When an insect crawls across the surface of the trap and touches a hair, not just once, but twice, the trap snaps shut to capture the prey. The plant releases digestive juices that contain enzymes to help speed up decomposition and the release of minerals.
- **Modified leaves to form pitchers that trap prey:** Pitcher plants, such as the one in Figure 11-4, have modified leaves that form tall columns for trapping prey. (For the details on how pitcher plants, such as the cobra lily, trap and kill their prey, see Chapter 21.)
- **Glands that produce sticky substances to trap prey:** Plants such as the sundew, shown in Figure 11-4, have elongated glandular structures that secrete a sticky, sweet mucus. The sweet mucus attracts insects that then get trapped in it and either die from exhaustion as they try to escape or drown in the mucus itself. The glands also secrete digestive enzymes that break down the body of the prey, releasing minerals to the plant.

Because carnivorous plants are so cool, many people want to have one in their plant collection. This has led to overharvesting of these plants in some fragile environments. So, if you want to have a Venus flytrap or other carnivorous plant of your very own, be sure to buy from a company that breeds the plants for themselves, rather than one that collects from the wild.



a. Venus fly trap

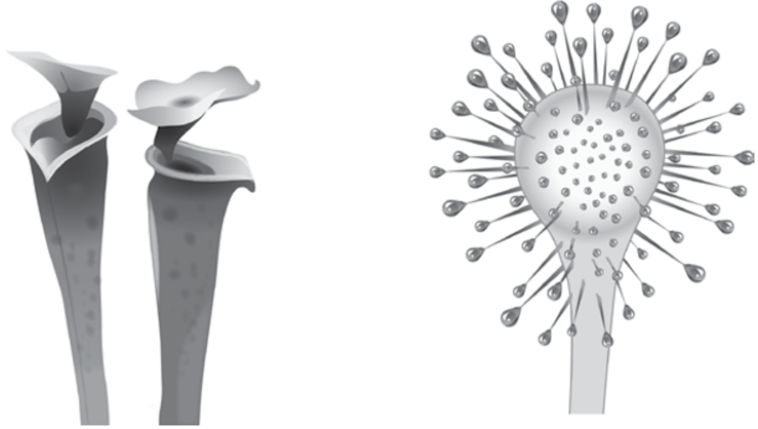


FIGURE 11-4: Adaptations of carnivorous plants.

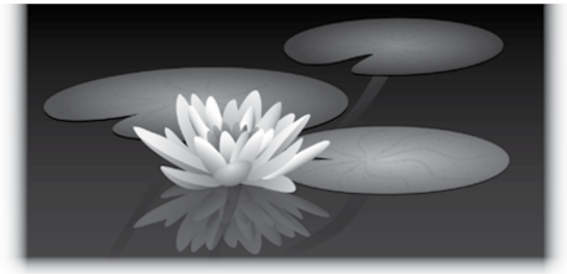
b. Pitcher plant

c. Sundew

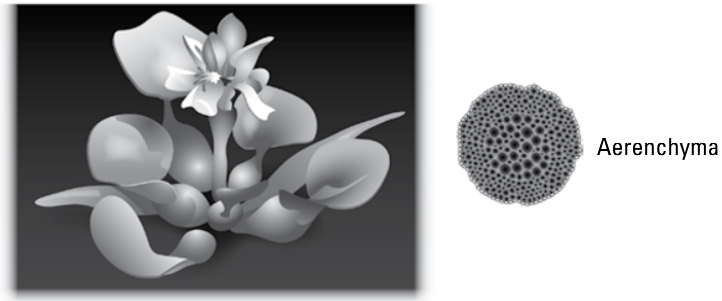
Aquatic plants

Aquatic plants obviously have access to plenty of water and dissolved minerals, so their challenge is to find a way to balance life in the water with access to sunlight. Evolution has led to plants (see Figure 11-5) that utilize a variety of strategies for making life on the water work:

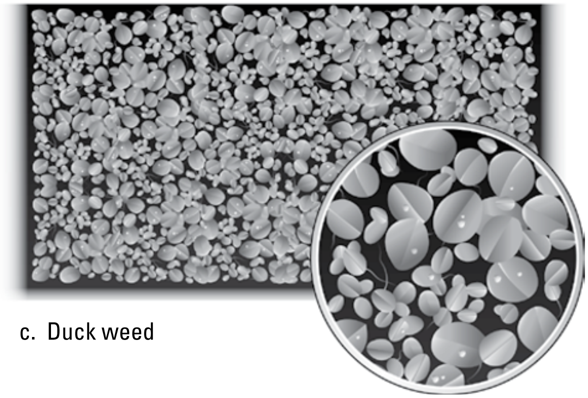
- **Flat, floating leaves:** Water lilies are a familiar example of this strategy. Water lilies are rooted in the sediment, but their leaves have very long petioles that stretch to the surface of the water. The leaves themselves are flat so that they can float easily. The petioles contain aerenchyma tissue with lots of air spaces to help the leaves float. (For details on aerenchyma, check out plant tissues in Chapter 2.)
- **Buoyant tissues:** Water hyacinths have bulbous, spongy petioles that are full of aerenchyma. The petioles are so buoyant that the whole plant floats. The short roots of water hyacinth extend into the water, but don't anchor the plants in the sediment.



a. Water lily



b. Water hyacinth



c. Duck weed

FIGURE 11-5: Adaptations of aquatic plants.

- **Small size, rounded shape:** The aquatic plant duckweed is the smallest and fastest growing of all the flowering plants. They have no true leaves or stems, but are just small, rounded bodies that float on the water.

4

The Wide, Wonderful World of Plants

IN THIS PART . . .

Visualize the relationships between plants and other organisms using phylogenetic trees

Discover how the earliest plants colonized the land

Explore the lives of plants that make seeds

Find out how fungi like mushrooms are very different from plants

IN THIS CHAPTER

- **Discovering the three domains of life**
- **Reading phylogenetic trees**
- **Naming organisms**
- **Using a dichotomous key**

Chapter 12

The Tree of Life: Showing the Relationships between Living Things

Life on Earth is wonderfully abundant and diverse. People, such as scientists, farmers, gardeners, and nature lovers, who are interested in living things look for ways to organize what they know. An important part of that organization is naming each organism and observing the characteristics that make each organism unique. This chapter introduces the methods that scientists use when naming and classifying organisms and gives examples of how to read phylogenetic trees and use dichotomous keys.

Examining the Branches of the Tree of Life

Chances are the members of your family have more things in common with each other than they do with people who aren't related to you — you may have similarities in eye and skin color, a certain shape to your noses, or a tendency to be tall. You have more in common with your relatives than you do strangers because your family all share certain genes in common. You got your DNA from your parents, who got theirs from their grandparents. Some of this same DNA got passed to your siblings, cousins, aunts, and uncles, leading to your *shared characteristics*, the characteristics that you have in common.

In the same way that you can recognize similarities between your family members, you can probably pick out relationships between other kinds of living things on Earth. Cats and dogs may be different, but they both have fur, four legs, and a tail and are clearly more like each other than they are like a rosebush. So, if you had to draw a family tree of life on Earth, you'd probably put cats and dogs close together on a branch of the tree and pretty far away from the rosebush branch. Scientists use this same basic method of looking for similarities between living things in order to figure out the relationships between all life on Earth.

REMEMBER

Scientists assume that the more shared characteristics two organisms have with each other, the more closely related they are to each other.

The types of clues scientists use to figure out relationships include

- **Physical structures:** The structures that scientists use for comparison may be large, like the production of cones versus flowers, or very small, like the presence of a wall around the cell. For example, cone-bearing plants are more closely related to each other than are flowering plants. Botanists consider reproductive structures like cones and flowers to be especially important for determining relationships among plants.
- **Chemical components:** Some organisms make unique chemicals. All plants, for example, make cell walls made of cellulose and many produce starch as their main energy storage molecule.
- **Genetic information:** An organism's DNA determines its traits, so by reading the DNA, scientists go right to the source of differences between species. Even organisms that might seem to be incredibly different — such as you and a carrot — have traits in common.

Digging into the three domains

REMEMBER

All cells on Earth contain ribosomes for making proteins. So, scientists can read the genes that contain the blueprints for ribosomes from any type of cell on Earth and use the similarities and differences between the genes to build a family tree for all life on Earth. The genes scientists use most often for looking at relationships are called *ribosomal RNA genes* (rRNA genes).

REMEMBER

When scientists compared all life on Earth by reading the codes of ribosomal RNA genes, they discovered that living things fall into three main groups. Scientists call the three main groups of life *domains*.

Figure 12-1 shows the three domains of life that make up the main branches of the family tree of life on Earth:

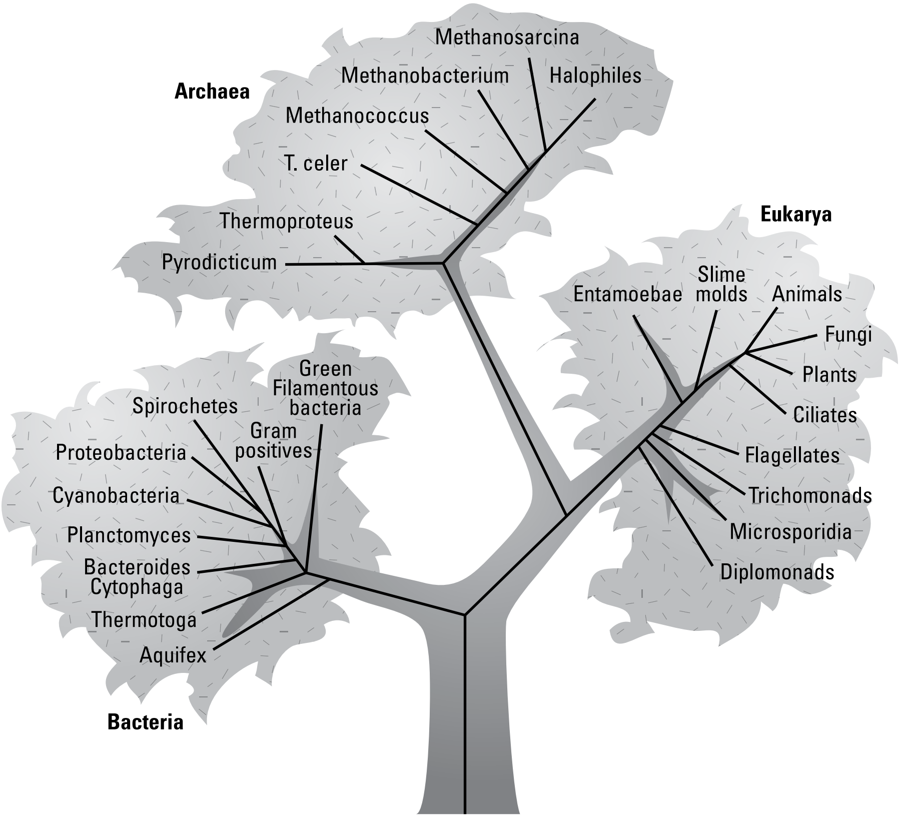

Archaea
Methanosarcina
Methanobacterium
Halophiles
Methanococcus
T. celer
Thermoproteus
Pyrodicticum
Eukarya
Entamoebae
Slime molds
Animals
Fungi
Plants
Ciliates
Flagellates
Trichomonads
Microsporidia
Diplomonads
Green Filamentous bacteria
Spirochetes
Gram positives
Proteobacteria
Cyanobacteria
Planctomyces
Bacteroides Cytophaga
Thermotoga
Aquifex
Bacteria

FIGURE 12-1: A phylogenetic tree of life based on rRNA genes.

- **Archaea:** Archaeans are prokaryotic organisms that are found in just about every environment on Earth, including harsh environments like hot springs, salt lakes, and hydrothermal vents. (For the scoop on prokaryotic cells, check out Chapter 2.) Although archaeans physically resemble bacteria, the two groups of prokaryotes have some fundamental chemical and genetic differences that indicate that they're unique types of cells.
- **Bacteria:** Bacteria are prokaryotic organisms that mostly get noticed by people because some of them cause disease. Although some bacteria are truly

dangerous to human health, most bacteria are actually beneficial to humans and all other types of life on Earth. Bacteria are nature's recyclers — they break down dead material and recycle nutrients that other organisms need to live. Many bacteria are plant-like in the sense that they're photosynthetic — in fact, bacteria and algae perform over half the world's photosynthesis! (To learn more about these organisms, see Chapter 13.)

- **Eukarya:** Plants and people — as well as other animals, fungi, and lots of microorganisms — belong in this domain. All organisms in Eukarya have eukaryotic cells. (For details on the eukaryotic cell, flip to Chapter 2.) So, even though you're physically very different from plants, they're your very distant relatives!

Exploring the past through phylogenetic trees

The trees that scientists draw to represent relationships between living things, like the ones in Figures 12-1 and 12-2, are called *phylogenetic trees*. Scientists use computer programs to draw the trees based on their observations of structure, chemistry, and the gene sequences of individual species or related groups called *taxa*.

REMEMBER

A *taxon* (plural: *taxa)* is a group of related organisms in a biological classification system.

The computer programs compare the similarities between different species, drawing the trees so that the branches of the most similar groups are closest together and sketching in how the different groups might have descended from their ancestors.

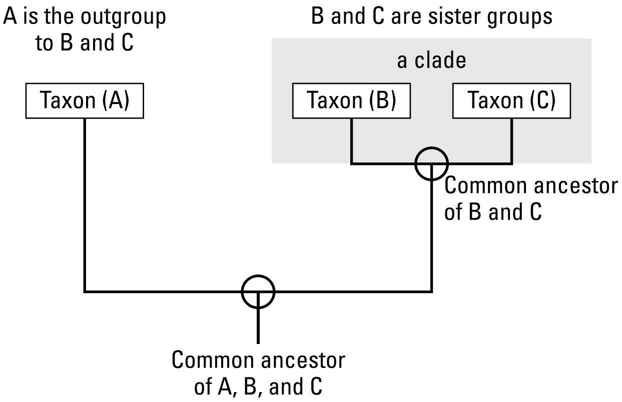

A is the outgroup to B and C
B and C are sister groups
a clade
Taxon (A)
Taxon (B)
Taxon (C)
Common ancestor of B and C
Common ancestor of A, B, and C

FIGURE 12-2: Reading a phylogenetic tree.

REMEMBER

Phylogenetic trees not only show how closely related organisms are, they also help map out the evolutionary history, or *phylogeny,* of life on Earth.

Just like your family began a long time ago with your original human ancestors, scientists believe that all life on Earth began from one original *universal ancestor* after the Earth formed 4.5 billion years ago. Most phylogenetic trees reflect this idea by being *rooted,* meaning they're drawn with a branch that represents the common ancestor of all the groups on the tree. In Figure 12-1, earlier in this chapter, the unlabeled branch at the bottom of the tree represents the common ancestor for all organisms on the tree, which in this case is the universal ancestor of all life on Earth.

To read a phylogenetic tree like the one in Figure 12-2, look for the following information:

- The tips of the branches represent the species or other taxa that the scientist is comparing. Figure 12-2 shows a tree for three taxa: taxon A, taxon B, and taxon C.
- Branches meet at points called *nodes* that represent the common ancestor of the two taxa. Scientists call groups that branch out from the same common ancestor *sister groups*. In Figure 12-2, group B and group C are sister groups.
- An ancestor plus all its descendants form a *clade*. Figure 12-2 shows the clade for taxon B and C.
- Scientists call groups that branch from the base of the tree and are separate from the other groups *outgroups*. Scientists often deliberately include observations about a group that isn't very closely related to the group being studied in order to give a tree an outgroup. When the computer program has to include the outgroup, it helps give the tree scale by showing the group being studied in relationship to the larger picture of other kinds of life on Earth.

Organizing Life

The three domains represent the three largest, and most distantly related, groups of living things on Earth — in other words, the three biggest branches on the family tree of life. But each of those big branches has many smaller branches that represent related groups within the domains. Each living thing is classified by its characteristics into a *taxon.*

Developing a system

Scientists who name and organize living things practice the branch of science called *systematic biology,* or *systematics*. The science of systematics includes subdisciplines called *taxonomy,* which is the naming of living things, and *classification,* which is the organization of living things. Systematic biologists organize life on Earth not just by the domains, but by subcategories within the domains. All the categories and subcategories form a *taxonomic hierarchy* that shows the degree of relationship between groups.

REMEMBER

The taxonomic hierarchy for living things, from the largest, most inclusive group to the smallest, least inclusive group is Domain, Kingdom, Phylum, Class, Order, Family, Genus, Species.

TIP

You can think of the taxonomic hierarchy as a set of nesting boxes. You'd start with three big boxes representing the three domains and sort all the organisms on Earth into those three boxes. Then, you'd take one of the boxes — box Eukarya, for example — and look at how you could further organize all the living things you'd put into that box. You'd see that all animals had certain things in common that were different from the rest of the organisms, so you'd put all the animals together in a smaller box inside the big Eukarya box. Similarly, you could put all the plants together in a second smaller box, all the fungi into a third box, and all the protists into a fourth. Then, you could pick up the animal box, look inside and decide how to sort the animals further into even smaller boxes that would fit inside the animal box, and so on, until you'd organized all the living things in each box as much as you possibly could.

In traditional, or *classical systematics,* organisms are sorted into groups primarily based on their similarities in structure (morphology), development, and metabolism. The more similar two organisms are, the more likely they are to be placed together in a category. The relative position of two organisms within the taxonomic hierarchy suggests the degree of their relationship. For example, you and a carrot are both in domain Eukarya, so you definitely have some things in common, but you have more things in common with organisms that are also in the animal kingdom, like a dog. Table 12-1 gives you an idea of how the taxonomic hierarchy works by comparing the taxonomy of you, a dog, a carrot, and the bacterium, *E. coli*.

Of the organisms listed in Table 12-1, you have the most in common with a dog. You're both animals that have a central nervous chord (phylum Chordata), and you're both mammals (class Mammalia), which means you have hair and the females of your species make milk. However, you also have many differences from a dog, including the tooth structure that separates you into the order Primates and a dog into the order Carnivora. If you compare yourself to a plant, you can see that you have certain features of cell structure that place you together in domain Eukarya, but little else in common. Two organisms that are together in the same species are the most similar of all.

TABLE 12-1 A Comparison of the Taxonomy of Several Species

Taxonomic Group	Human	Dog	Carrot	E. coli
Domain	Eukarya	Eukarya	Eukarya	Bacteria
Kingdom	Animalia	Animalia	Plantae	Eubacteria
Phylum	Chordata	Chordata	Anthophyta	Proteobacteria
Class	Mammalia	Mammalia	Rosopsida or Eudicots	Gammaproteobacteria
Order	Primates	Carnivora	Apiales	Enteroacteriales
Family	Hominidae	Canidae	Apiaceae (Umbelliferae)	Enterobacteriaceae
Genus	*Homo*	*Canis*	*Daucus*	*Escherichia*
Species	*Homo sapiens*	*Canis familiaris*	*Daucus carota*	*Escherichia coli*

TIP

People have lots of funny sayings to help them remember the taxonomic hierarchy. My personal favorite, because it's so hard to forget, is Dumb Kids Playing Chase On Freeways Get Squished. The first letter of each word in the sentence represents the first letter of a category in the taxonomic hierarchy and will help you remember the order of the categories. If you don't like this particular saying, just search the Internet for "taxonomic hierarchy mnemonic," and you'll find many others.

WARNING

In classical botany, the term *division* was used instead of phylum. Most biologists have switched to using phylum for plants in order to be consistent among all living things, but some botanists still use the older term division.

Now that scientists have the ability to read the DNA of organisms, they are gaining new understandings of the relationships between taxa of life on Earth. By going straight to the genes, scientists can compare organisms that don't have a lot of morphological characteristics, like prokaryotes, or see through confusing situations, such as two unrelated organisms having a similar structure due to convergent evolution (for more on convergent evolution, flip back to Chapter 11). New information is being obtained at a rapid pace, and modern systematic biologists are still working on how best to combine the new information on phylogeny with the old system of using the categories of the taxonomic hierarchy.

Ideally, scientists want to create a taxonomic system that's easy to use and that reflects the evolutionary history of organisms. In order for taxonomic groups to reflect relationships, the groups have to be carefully constructed:

- **Ideal taxonomic groups are *monophyletic,* meaning that all the organisms within the group share a common ancestor and all descendants of that ancestor are included in the group.** For example, you could create a monophyletic group by grouping taxon A, B, and C all into the same family.
- **Some taxonomic groups are *paraphyletic*, meaning that all the organisms in the group share a common ancestor, but some of the descendants of that ancestor aren't included in the group.** For example, if you grouped taxon B and C from Figure 12-2 into one family and put taxon A into a different family, then the family containing B and C would be paraphyletic. Both B and C share a common ancestor, but they also share a common ancestor with A, which is being left out of the family. Paraphyletic groups do exist within current taxonomic systems because they sometimes make it easier to discuss certain groups.
- **Taxonomic groups that are *polyphyletic* (meaning that the organisms within the group don't share a common ancestor but are grouped together because of a common characteristic) should be avoided.** Polyphyly would occur if you grouped the cyanobacteria from domain Bacteria and plants from domain Eukarya into one taxonomic group based on the fact that they're all photosynthetic. Look at Figure 12-1 and imagine drawing a circle around these organisms to create a group, and you'll see that the group makes no sense in evolutionary terms — although cyanobacteria and plants share a common ancestor way back in evolutionary time, putting just them into a group completely ignores many of their closer relatives.

Defining plants

In the classic taxonomic hierarchy, organisms within each domain are broken up into categories called *kingdoms.* Domain Eukarya currently contains four kingdoms: Animalia (animals), Plantae (plants), Fungi (mushrooms, molds, yeast), and Protists (mostly microbial eukaryotes).

Most modern botanists include organisms in Kingdom Plantae if they have the following characteristics:

- **Eukaryotic** (see Chapter 2)
- **Photosynthetic,** with the pigments chlorophyll *a* and chlorophyll *b* (see Chapter 5)

- Store food as **starch** and have **cellulose** in their cell walls (see Chapter 2)
- During cell division, the formation of a new cell wall is aided by a **phragmoplast** (see Chapter 9)
- Develop from **embryos** supported by maternal tissue

REMEMBER

Based on this definition of plants, combined with historical precedent, the plant kingdom is usually defined as containing land plants, from mosses that don't have vascular tissue (see Chapter 14) to cone-bearing plants (see Chapter 15) and flowering plants (see Chapter 16) that do have vascular tissue.

This definition of the plant kingdom, however, may change as a result of comparisons of the DNA of land plants and the green algae.

REMEMBER

Comparisons of genes in land plants and green algae support the idea that green algae are the closest relatives of land plants, something that botanists have believed for centuries based on comparisons of morphology, metabolism, and development.

However, the information from DNA studies also showed that one group of green algae, the charophytes, are a sister group to the land plants. In other words, if you refer to Figure 12-2, you could imagine taxon B as the charophytes and taxon C as the land plants, which are sometimes called *embryophytes.* The charophytes and the land plants share a common ancestor. So, if scientists put the land plants in one kingdom (Plantae) and put the charophytes in another kingdom (Protista), then the kingdoms are paraphyletic and don't really reflect the evolutionary relationships between these organisms.

REMEMBER

Because land plants and green algae form a monophyletic group, many botanists are in favor of including green algae in the plant kingdom.

It's not yet clear how botanists will reconcile the classical definition of the plant kingdom with the more recent understanding of the phylogeny of plants. Some botanists have proposed leaving things as they are, placing charophytes and embryophytes in different taxonomic groups. Others have proposed placing them together in a single phylum called the Streptophyta. In this book, I use the classical definition of plants as stated in this section, but acknowledge the close relationship of charophytes to the land plants.

Naming the Rose (and Other Living Things)

People have been studying, naming, and classifying plants for thousands of years. One early major attempt was made by Theophrastus, a student of Aristotle and Plato. In the third century BC, Theophrastus published a classification of nearly 500 plants that scientists continued to use and add onto until the 18th century, using the structure of leaves, stems, fruit, and flowers to organize and name plants. Related plants were grouped into taxa called *genera* (singular: genus). Each plant was given a name that consisted of the Latin name for the genus, plus a short description, also in Latin, of its distinguishing characteristics. This practice produced some pretty long names, such as *Mentha floribus spicatis, foliis oblongis serrates,* which represented a mint with a spike of flowers, and oblong, saw-toothed leaves.

Fortunately, in the 1750s, a Swedish naturalist named Carl Linnaeus, who did a huge amount of work on classifying plants and animals, streamlined the naming of organisms by proposing an abbreviated name for each species consisting of just two words. In Linnaeus's system, the abbreviated name (called a *binomial* because it contains only two words) for the mint described in the previous paragraph would be *Mentha spicata*. In time, Linnaeus and scientists after him dropped the longer plant names in favor of the shorter ones, formally adopting a system of binomial nomenclature.

REMEMBER

In *binomial nomenclature,* the first part of an organism's name is the genus, and the second part of the species name is the *specific epithet,* or species name.

The rules for using binomial nomenclature are

- The genus is always capitalized.
- The specific epithet is never written without the genus, although the genus can be abbreviated by just the first letter.
- To indicate that the name is the official scientific name, both the genus and species are either italicized or underlined.
- The name of the person who named the organism may also be included after the name, either as a full last name or the first letter of the last name.

According to these rules, then, humans may be correctly identified as *Homo sapiens* or *H. sapiens* (or *H. sapiens* L. if you want to show that it was Linnaeus himself who first named this species). A carrot would be *Daucus carota* or *D. carota*.

All scientists around the world use the same scientific names for organisms, which helps them communicate no matter which language they speak or where they live. Although many plants that have blue bell-shaped flowers might commonly be called bluebells, they may not actually be related — in other words, a bluebell in England may be different from a bluebell in Texas. In order to share information and new discoveries, scientists need to be sure that they're talking about the same organism. So, if you find a bluebell in Texas and call it *Eustoma grandiflorum*, a scientist will know exactly which flower you're talking about.

REMEMBER

If you were out walking in a field and you found a plant with a blue bell-shaped flower, you could figure out exactly what to call it using a dichotomous key. *Dichotomous keys* use a series of questions, each of which has two choices, to help a person identify the name of an organism.

Many people who enjoy hiking or bird-watching use a dichotomous key to help them identify plants and animals. Some keys designed for recreational use may use other types of organization — for example, grouping all plants with red flowers into one section of a book, and all plants with blue flowers into another. But many keys, especially those used by botanists, rely upon the dichotomous organization shown in Table 12-2.

TABLE 12-2 A Dichotomous Key

Numbered Pairs of Traits to Consider	Description of Plants to Choose From	Directions for Next Move
1a.	Flowers blue to pink, in open or dense clusters	Go to 2
1b.	Flowers white, yellow or blue, in coiled clusters	Go to 3
2a.	Stems ascending to upright; flowers 9–19 mm long	*Mertensia paniculata*
2b.	Stems sprawling; flowers 4–12 mm long	*Mertensia maritime*
3a.	Flowers blue; nutlets round, smooth, and shiny	*Myosotis laxa*
4a.	Lower leaves opposite, upper leaves alternate; flowers white	*Plagiobothrys scouleri*
4b.	All leaves alternate; flowers yellow or white with a yellow center	Go to 5
5a.	Flowers yellow; nutlets wrinkled and warty	*Amsinckia menziesii*
5b.	Flowers white with a yellow center; nutlets minutely bumpy or smooth	*Cryptantha intermedia*

Adapted from Plants of the Pacific Northwest Coast (Lone Pine Publishing) by Jim Pojar and Andy MacKinnon.

To use a dichotomous key, follow these steps:

1. **Read the first pair of questions or statements and decide which of the two choices fits your plant.**

   In Table 12-2, the first choice asks you to choose based on the color and arrangement of the flowers.

2. **Follow the direction at the end of the option you choose.**

   If you were looking at a plant with blue flowers in coiled clusters, you'd choose option 1b. When you look at the end of option 1b, the direction is to go to 3.

3. **Skip over any statements that you're not directed to go to.**

   If you choose option 1b in Step 2, you'd go straight to the pair of options at 3, skipping over number 2 in Table 12-2 entirely.

4. **Read the next pair of questions or statements and decide again which choice best fits your plant.**

   The choices at 3 ask again about flower color and include some details about the fruit (a nutlet). If your flower is blue, you'd choose option 3a.

5. **Repeat these steps until you arrive at the name of your plant.**

   The choice of option 3a leads you to the name *Myosotis laxa,* which is the scientific name for your plant.

In order to use a plant key to identify a plant, you need to make careful observations of the plant characteristics like leaf shape and arrangement (discussed in Chapter 3) or the detailed structure of flowers (presented in Chapter 4). Botanists have developed a large vocabulary to precisely describe the nuances of plant structures. This vocabulary can be a little daunting at first. In this book, I present some of the most commonly used terms, but if you become seriously interested in identifying plants and find yourself confronted with lots of unfamiliar terminology, you can pick up a reference book like *Plant Identification Terminology* by James G. Harris and Melinda Woolf Harris to help you choose the correct terms for what you are observing when you look at a particular plant.

IN THIS CHAPTER

- **Exploring the origin of photosynthesis**
- **Discovering where plants got their chloroplasts**
- **Looking at the ancestors to land plants**

Chapter 13

Precursors to Plants: Bacteria, Protists, and Algae

Long before there were land plants, microbes were the food producers on planet Earth. In fact, scientists now think that photosynthesis has been happening on our planet almost since the very first cells appeared. In this chapter, I take a look at the evidence for the origin of photosynthesis and then trace a path from the very first photosynthetic cells to the closest relatives of land plants.

Bacteria Can Be Green, Too

Most people think of bacteria in terms of something that can make us sick, but in reality, only a very small percentage of bacteria are human pathogens (the spirochete shown in Figure 13-1, for example, causes syphilis). You probably know that you have bacteria living in your gut that help with your digestion (like the

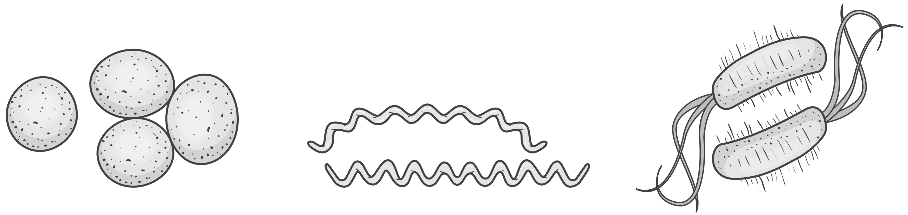
Escherichia coli shown in Figure 13-1), but did you know you have bacteria all over every surface of your body (like the *Staphylococcus* in Figure 13-1)? In fact, you have more bacteria living on you than you have cells of your own! Don't panic, though, these bacteria are generally helpful to you and even prevent other, more harmful bacteria from moving in.

On our planet, bacteria are more than just helpful — they're absolutely essential to all other life. They are the invisible workhorses in our ecosystems. Here's just a short list of some of the things they do:

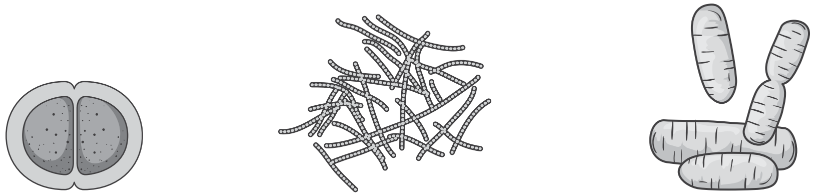
- They capture nitrogen gas out of the air, converting it to forms of nitrogen that plants and other organisms can use. All organisms rely on this *nitrogen fixation* to get nitrogen for their proteins and DNA. (For more on this process, check out the nitrogen cycle in Chapter 20.)
- Along with fungi (see Chapter 17), they are nature's recyclers, eating the dead in a process called *decomposition* (discussed more in Chapter 20). As they break down dead organisms, they release minerals into the soil and return carbon to the air as carbon dioxide (CO_2). Without decomposition, the bodies of the dead wouldn't get returned to the necessary atoms and molecules that are re-used by the living.
- Bacteria seem insignificantly small to us, but other tiny organisms think they are the perfect size for a meal. And then slightly larger organisms eat the tiny, and so on. In other words, bacteria are part of the food webs of our ecosystems, which ultimately lead to food for larger organisms (see Chapter 20 for more on food chains and food webs).
- And then, last but not least, some bacteria can actually make food from CO_2 and an energy source, just like plants. Some of them photosynthesize and some, in the absolute darkness at the bottom of the ocean, make food using CO_2 and chemicals that leak out of hydrothermal vents.

Inventing photosynthesis

When people think about photosynthesis, they usually think about plants, especially trees. They are big, they are beautiful (to many of us), and we know they make the oxygen (O_2) we need to breathe. So, would it surprise you to learn that at least half of the world's photosynthesis is done by microbes that are too small to see without a microscope? Or, how about the fact that it was actually microbes — specifically bacteria — that invented photosynthesis in the first place?



Gram-positive bacteria Spirochetes Proteobacteria



Chroococcus tenax
Cyanobacteria

Chloroflexus aggregans
Green filamentous bacteria

Bacteroide

FIGURE 13-1: Examples of bacteria.

To put this story in context, we have to go back 4.5 billion years to when the Earth first solidified. Scientists have used several approaches to try and piece together the history of life on Earth:

- **The oldest fossils, which look very similar to modern day bacteria, appear in rocks that date to 3.5 billion years ago (bya).** Scientists look for fossils like these by making very thin slices of rock samples and looking at them on a microscope. From this, scientists conclude that cellular life first appeared on Earth 3.5 bya and that these cells were prokaryotic in structure. (Prokaryotic cells, like those of bacteria, lack nuclei and organelles.)
- **Ancient bacteria developed the ability do a type of photosynthesis that doesn't produce oxygen possibly as early as life first began 3.5 bya**. Bacteria exist today that do this type of photosynthesis, which is called *anoxygenic photosynthesis*. Some modern bacteria, like the green filamentous bacteria shown in Figure 13-1, use sulfur compounds like hydrogen sulfide (H_2S) rather than water (H_2O) as their source of electrons. Plants and microbes produce oxygen from *oxygenic photosynthesis* when they remove hydrogen (H) from H_2O, producing as O_2 as waste (for a review on this type of photosynthesis, head back to Chapter 5). When bacteria remove electrons from sulfur compounds, they release sulfur as waste rather than oxygen.
- **Oxygen didn't appear in Earth's atmosphere until about 2.4 bya.** Scientists detect the presence of atmospheric oxygen by examining the iron content of rocks. When sediments have contact with oxygen, the iron in those sediments *oxidizes*, or rusts. When scientists examine rocks formed before 2.4 bya, the iron in the rocks is black, not red, which tells scientists that the rocks formed in an oxygen-free environment.

- **The first photosynthetic bacteria to produce O_2 during photosynthesis were probably cyanobacteria.** Some of the fossils from 3.5 bya resemble cyanobacteria, like the ones shown in Figure 13-1. As cells reproduced and changed, the cellular machinery they used to photosynthesize changed with them. At some point, a photosynthetic bacterium starting using H_2O as their source of electrons, producing O_2 as waste. Scientists used to think this must have happened about 2.4 bya when oxygen first started accumulating in the atmosphere. However, a group of scientists recently suggested that bacteria might have started switching much earlier, but only sporadically, so that the O_2 didn't accumulate. They based their conclusion on a comparison among several groups of bacteria of the DNA sequence for a protein necessary for oxygenic photosynthesis.

REMEMBER

Another difference between the bacteria that do anoxygenic photosynthesis and the cyanobacteria that do oxygenic photosynthesis is in the pigments they use to capture light energy. Bacteria that don't produce oxygen have a pigment called *bacteriochlorophyll*, which is similar to, but not the same as, the chlorophyll molecules found in plants. Cyanobacteria have *chlorophyll a*, which is also found in land plants, as well as pigments called *phycobilins*, which give them a sort of blue-green color (cyanobacteria are also called *blue-green bacteria* or even *blue-green algae*). To learn more about the role of these pigments in photosynthesis, flip back to Chapter 5.

Becoming chloroplasts

Although scientists still have questions about exactly which microbes invented photosynthesis and when it all happened, they all pretty much agree on how plants learned to do it: their ancient single-celled ancestor ate a cyanobacterium and didn't digest it. The cyanobacterium continued to photosynthesize inside this ancestral cell. Over billions of years of evolution, the cyanobacteria changed and became what we know today as chloroplasts.

If you think this sounds like a crazy story, you aren't alone. When scientists first proposed this idea, other scientists either ignored them or scoffed at their ideas. But over the years, more and more evidence accumulated to support this idea, and today it is considered a scientific *theory*, which means that scientists agree that the idea has strong supporting evidence.

The Serial Endosymbiotic Theory for the Origin of the Eukaryotic Cell (SET, shown in Figure 13-2) explains how eukaryotic cells evolved from prokaryotic ancestors (for a review of eukaryotic cells head back to Chapter 2):

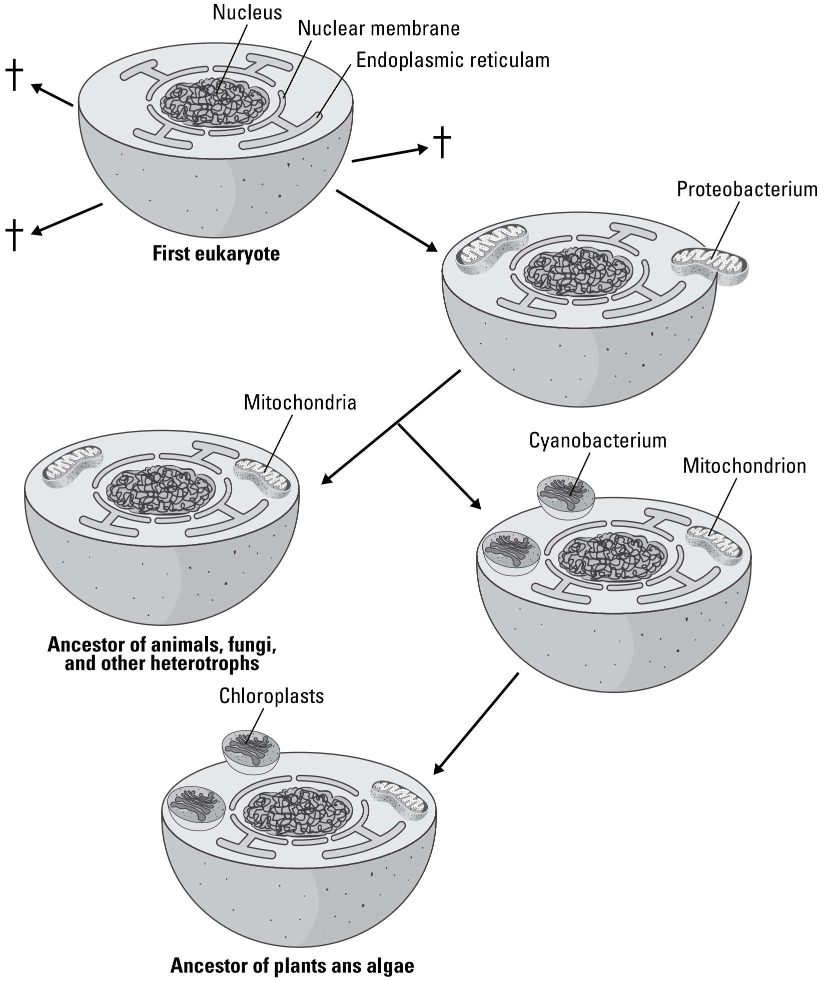

Nucleus
Nuclear membrane
Endoplasmic reticulam
†
†
†
First eukaryote
Proteobacterium
Mitochondria
Cyanobacterium
Mitochondrion
Ancestor of animals, fungi, and other heterotrophs
Chloroplasts
Ancestor of plants ans algae

FIGURE 13-2: The serial endosymbiotic theory for the origin of mitochondria and chloroplasts.

- **First, the ancestor of the eukaryotic cell captured a bacterium that could do cellular respiration.** Instead of one cell killing the other, the two lived together, which scientists call *symbiosis* (which I talk about in Chapter 20). Symbiosis happens all the time in nature, so this isn't that remarkable. What is unusual is that the partnership became permanent, with the bacteria evolving into the organelles we call mitochondria. (Which means right now, in each and every one of your cells, you have descendants of ancient bacteria!)
- **Next, some of the descendants of the first partnership did it again: they captured a bacterium that could do photosynthesis.** The photosynthetic bacterium joined the symbiotic arrangement, and over time evolved into the organelle we call the chloroplast. The eukaryotes that went through both symbiotic events were the ancestors of the plants we know today, which have both mitochondria and chloroplasts.

TECHNICAL STUFF

The *SET* is supported by lots of evidence from several different types of scientific studies:

- Mitochondria and chloroplasts both have double membranes, which is what happens when one cell wraps its membrane around another cell.
- Mitochondria and chloroplasts both have their own ribosomes, which are similar to prokaryotic ribosomes in structure.
- Mitochondria and chloroplasts both have their own chromosomes, which are similar to prokaryotic chromosomes in structure.
- The rRNA gene from the chromosomes of mitochondria and chloroplasts are more similar to the rRNA genes of bacteria (proteobacteria and cyanobacteria, respectively) than they are to rRNA genes from the nucleus of eukaryotic cells.

The Wild World of Protists

The merger of our ancient prokaryotic ancestors led to the creation of eukaryotic cells. Scientists aren't exactly sure when this event happened, but some of the oldest fossils that seem to be eukaryotes are about 1.8 billion years old. The earliest eukaryotes were single-celled organisms (fossils of multicellular eukaryotes don't start appearing until about 1.6 bya). Scientists today put single-celled eukaryotes into a very large kingdom called Protista (for more about kingdoms and classification, flip back to Chapter 12).

Kingdom Protista contains a very diverse collection of eukaryotes that don't fit into the kingdoms Plantae, Animalia, or Fungi. The protists include everything from crawling amoebas that grab and eat smaller organisms to diatoms that do photosynthesis and glide along in their little glass shells. Although the majority of protists are microscopic, some of them, like the red and brown seaweeds discussed later in this chapter, are multicellular and can grow to be very large. Protists are important in food webs as food-makers (autotrophs), predators, and prey.

REMEMBER

Because there are so many different distinct groups of protists, scientists often lump protists together based on their role in the ecosystem, calling photosynthetic protists *algae* and non-photosynthetic protists *protozoans*.

Here's a quick glimpse into the world of protists, as shown in Figure 13-3 (protists are so much fun, though, I highly encourage that you also look up some videos online):

- **Amoebae** can be found in several groups of protists. These single-celled organisms appear to crawl as they push out their cellular membranes to move around surfaces. They reach out with their membranes to bag their prey for digestion in a process called *phagocytosis.*
- **Euglenids** are single cells that can swim using flagella or move by a squirming motion. Many of them have chloroplasts and can do photosynthesis.
- **Slime molds** are found in two different groups of protists. They are sometimes found as single cells, but then at certain times, they will join together to form larger structures.
- **Diatoms** are lovely golden-brown photosynthetic cells that build box-like shells (called *tests*) made out of silica. They release slime trails that they use to glide around in their environment.
- **Ciliates** like *Paramecium* swim using the cilia that cover their entire surface. They eat bacteria and smaller microbes.
- **Dinoflagellates** have two flagella, one of which wraps around their shell. Many are photosynthetic. These are the organisms that cause "red tide," closing fishing and swimming because of their dangerous neurotoxin.

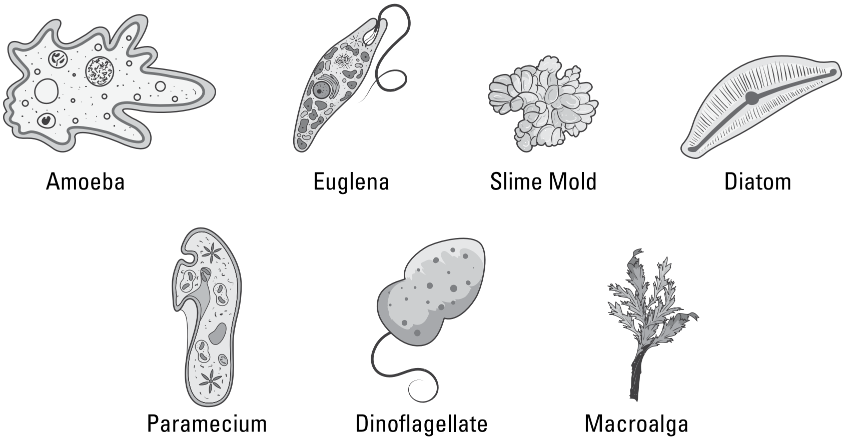


FIGURE 13-3: Examples of protists.

Seaweed: The Plants of the Ocean

Biologists place most of the organisms I introduce in this section into the Protista kingdom. I've given them their own section in this chapter because many of them are large and multicellular, so they're something you might notice when you visit a beach. However, based on evolution and DNA, these large algae are very closely related to some of the smaller protists mentioned in the preceding section.

Scientists distinguish between groups of photosynthetic organisms by which pigments they use to capture light energy for photosynthesis. The ability to make these pigments is coded into the DNA of an organism, so it helps show evolutionary relationships. Different pigments absorb different wavelengths of light (you can see examples in Chapter 5), which makes the algae different colors.

REMEMBER

Algae is a functional term that refers to an organism that is photosynthetic but doesn't fit into the plant kingdom. It isn't a term that reflects actual relationships based on DNA. To distinguish them from the microscopic algae, scientists sometimes refer to seaweeds as macroalgae.

Red algae

The red algae belong to the phylum Rhodophyta within the kingdom Protista. They contain chlorophyll along with a pigment called phycoerythrin, which gives them their reddish color. Red algae are important producers in marine environments. Other reasons they are important include:

- **Food**. Nori is made from dried sheets of the red alga Porphyra. People also eat dulce (*Palmaria palmata*) and carrageen moss (*Chondrus crispus*). Red algae are a great source of complex carbohydrates and antioxidants.
- **Medicine.** Scientists have made cancer-fighting medications from several red algae, including *Gracilaria foliifera*.
- **Thickeners.** If you read the label on your ice cream, nut milks, yogurt, and even frozen burritos, you might see the ingredient carrageenan. This common thickening agent is isolated from red algae. Another thickener from this group, called agar, is used in science labs all around the world to thicken the food used to grow cells like bacteria.
- **Tropical reefs**. The coralline red algae secrete a calcium carbonate shell around their cells, making them feel bony or crunchy to the touch. These algae are important reef-builders in Pacific atolls.

Brown algae

Scientists used to put the brown macroalgae in a phylum called Phaeophyta, but because of their close relationship to the diatoms (described earlier in this chapter) and another group of protists called water molds, some scientists argue that all these organisms be placed together into a larger group called the Chromista.

The brown algae and diatoms have the same pigments: chlorophylls a and c, plus pigments called fucoxanthins that give them their golden color. Unlike plants, they don't store food as starch.

The brown macroalgae are important producers in marine environments. Some of them get very large, up to almost 100 feet (30 meters)! They grow in large stands called kelp forests in the nearshore environment. These complex ecosystems are home to many species, including fish, sea otters, and sea urchins.

Kelp, like the *Nereocystis luetkean* shown in Figure 13-4, develop structures that help them grow successfully in the nearshore environment:

- **At the bottom of the alga, they grow a *holdfast* that allows them to attach to a solid surface like a rock.** This keeps them anchored on the ocean floor.
- **They grow upward via a simple stalk called a *stipe*.** This allows them to grow toward the surface of the water where there is plenty of light.
- **At the top, they grow an air-filled structure, the *float*.** The float keeps their photosynthetic organs, the *blades*, at water's surface. The blades are flat and wide to maximize light capture.

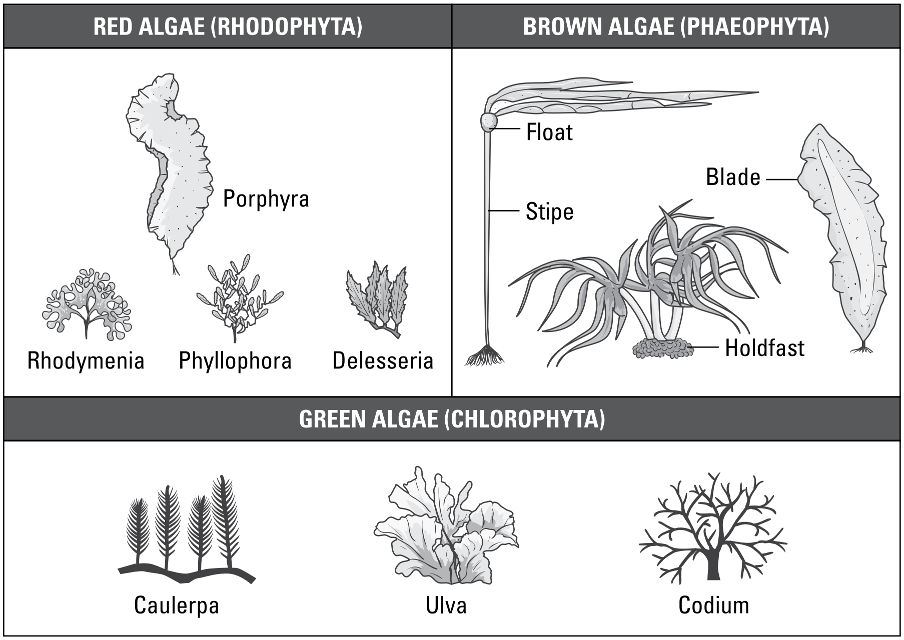

RED ALGAE (RHODOPHYTA)
BROWN ALGAE (PHAEOPHYTA)
Porphyra
Rhodymenia
Phyllophora
Delesseria
Float
Stipe
Blade
Holdfast
GREEN ALGAE (CHLOROPHYTA)
Caulerpa
Ulva
Codium

FIGURE 13-4: Macroalgae: Seaweeds.

Like the red algae, some brown algae are grown for food or for the extraction of thickeners. The thickener alginate is used in toothpaste, soap, ice cream, and other products.

Green algae

The green algae and land plants form a monophyletic group, so from an evolutionary standpoint they belong in the same taxon (see Chapter 12). For that reason, many biologists include the green algae in Kingdom Plantae. I'm choosing to go with the classical taxonomy that places the green algae in phylum Chlorophyta within the Protist kingdom, which is based on the distinction that plants have embryos supported by maternal tissue and green algae do not.

Because green algae and land plants are so closely related, they have many characteristics in common. Their primary photosynthetic pigments are chlorophylls a and b, and they store food as starch. The modern green algae that scientists think are most closely related to land plants are in the class Zygnematophyceae, which is a group of single-celled and filamentous green algae that are also sometimes referred to as charophytes.

Green algae are important producers in both marine and freshwater environments. A couple of species are also grown to produce nutritional supplements. *Chlorella,* which can be purchased as dried powder or pills, is a good source of vitamins and minerals and has been shown to have antioxidant and anticancer properties. *Dunaliella* is also grown as a nutritional supplement, in particular for the production of organic beta-carotene.

IN THIS CHAPTER

- Exploring how plants moved from the ocean to the land
- Discovering bryophytes
- Examining seedless vascular plants

Chapter 14

Examining the Forest Floor: Bryophytes and Seedless Vascular Plants

Lots of people love flowering plants, and many admire the beauty of tall pines and redwoods. But have you ever stopped to admire the smaller members of the plant kingdom, such as the mosses and liverworts that help carpet the forest floor? Have you ever walked through the woods or bracken and admired the feathery ferns? This chapter looks at the structure and life cycles of these somewhat lesser-known members of the plant kingdom, which have many features in common with their showier relatives.

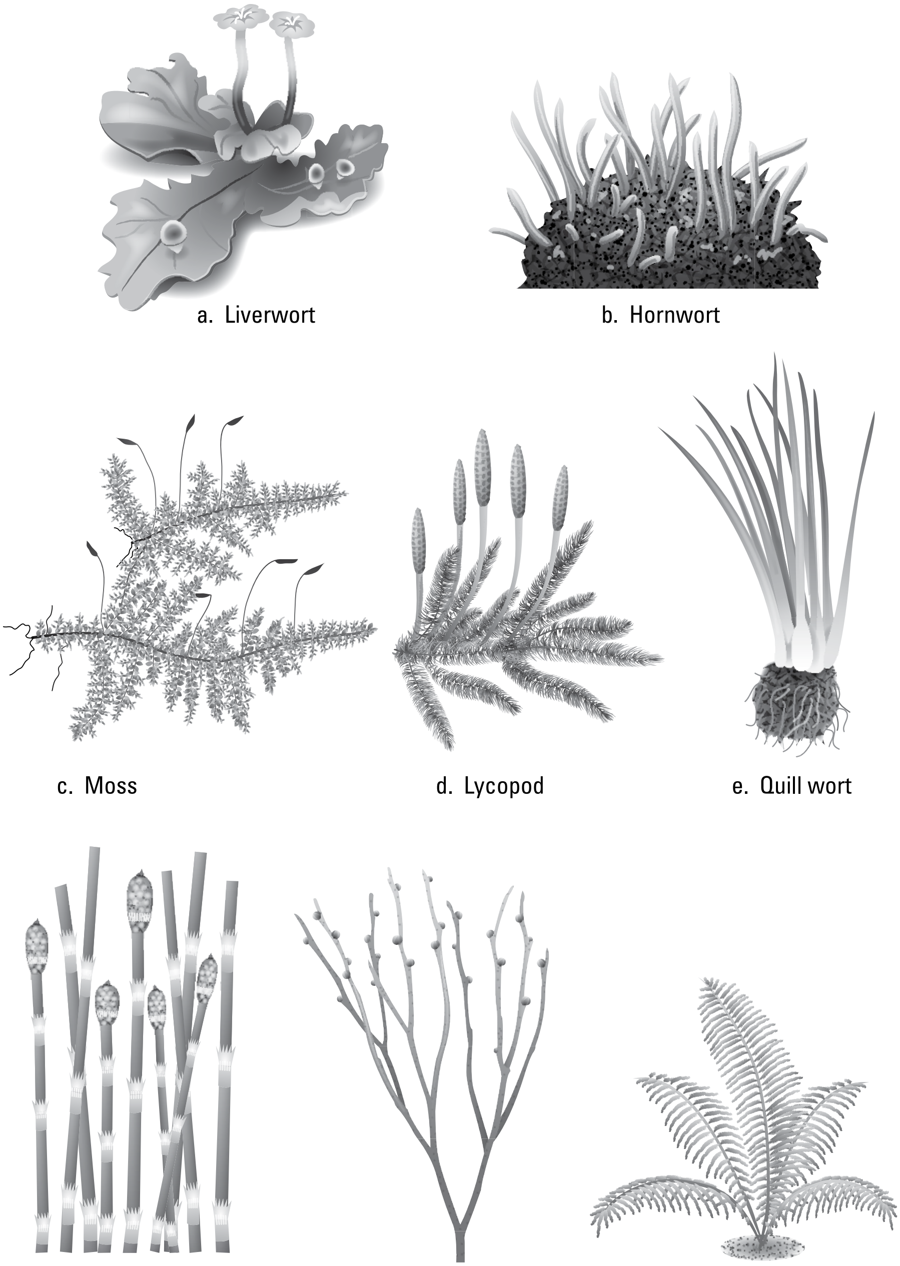
Moving onto the Land

The closest living relatives of land plants are green algae called charophytes (flip back to Chapter 13 for more on green algae and their relationship to land plants). The earliest plant fossils suggest that plants moved onto the land between 490 and 443 million years ago (during the Ordovician Period). Botanists think that the transition from life in water to life on land probably occurred in shallow ponds and marshes, where aquatic plants had access to water but also experienced higher levels of light. Plants that had characteristics that enabled them to move higher onto the land would benefit from the lack of competition for resources and could produce more offspring than the plants that had to stay totally submerged. Over long periods of time, a population of plants evolved to have features enabling it to survive on land.

The adaptations that enable plants to survive on land include both vegetative and reproductive adaptations:

- Vegetative adaptions include
  - Vascular tissue to transport water throughout the plant
  - A waxy cuticle that prevents plant tissues from drying out, but that contains stomates so that plants can still exchange gases with the atmosphere
  - Formation of a symbiotic association with soil fungi (mycorrhizae) that helped land plants acquire water and minerals from the soil
  - Protective pigments that help block ultraviolet radiation
- Reproductive adaptations include
  - Thick spore walls to protect reproductive spores from drying out
  - Tissues called gametangia that surround and protect gametes (eggs and sperm) from drying out
  - Embryos protected by maternal tissues

The first plants that colonized the land probably had all of these characteristics and were very similar to plants called bryophytes and seedless vascular plants (see Figure 14-1) that are alive today. Phylogenetic studies on the relationships between living plants support the idea that modern bryophytes and seedless vascular plants are descended from the earliest land plants.



a. Liverwort

b. Hornwort

c. Moss

d. Lycopod

e. Quill wort

f. Horsetail

g. Whisk fern

h. True fern

FIGURE 14-1: Bryophytes and seedless vascular plants.

Bryophytes: Nonvascular Plants

Bryophytes are small plants that typically grow in moist areas. The bryophytes that are most familiar to you are probably mosses, which can be found growing in forests all over the world. Rarer are the lovely, delicate liverworts you might find growing on the rocks near a waterfall or stream.

WARNING

Bryophyte and bryophytes are informal names for a diverse group of non-vascular plants. These terms aren't the same as Bryophyta, which is a formal taxon (phylum) that refers specifically to the true mosses. (See the upcoming section "Mosses: Phylum Bryophyta.")

Bryophytes, which are organized into three phyla, all have certain characteristics in common:

- The gametophyte generation is the dominant, or most visible, phase of the life cycle.
  - Structures called antheridia produce sperm, and archegonia produce eggs.
  - After fertilization, the zygote develops inside the archegonium, and the sporophyte remains dependent upon the gametophyte.
  - They release their spores from elevated sporangia.
- The structure of the plant body is simple and typically lacking vascular tissue like xylem and phloem.
- They require water for reproduction so the sperm can swim to the egg.
- The water content of the plant body is about equal to that of the environment. When conditions are dry, the plants dry out, but don't necessarily die. When conditions are wet, the plants begin to grow again.

Liverworts: Phylum Hepatophyta

Liverworts can be flat, lobed plants like the one shown in Figure 14-1a, or they can be leafy and look more like mosses. Liverworts got their name because people in the Middle Ages thought the lobed liverworts looked like the liver from a person — *wort* is an old word for *plant*, so *liverwort* literally means *liver plant.*

Structure of liverworts

REMEMBER

Botanists call the simple, flattened bodies of lobed liverworts *thalli* (singular: *thallus*). The thallus of a lobed liverwort is different on the top and the bottom (see Figure 14-2):

- The top surface has *pores* that are used for gas exchange. The pores remain open at all times.
- The lower surface has little root-like structures called *rhizoids* that are made from single cells. Rhizoids help anchor the liverworts to the ground. Some liverworts also have multicellular *scales* on their bottom surface.

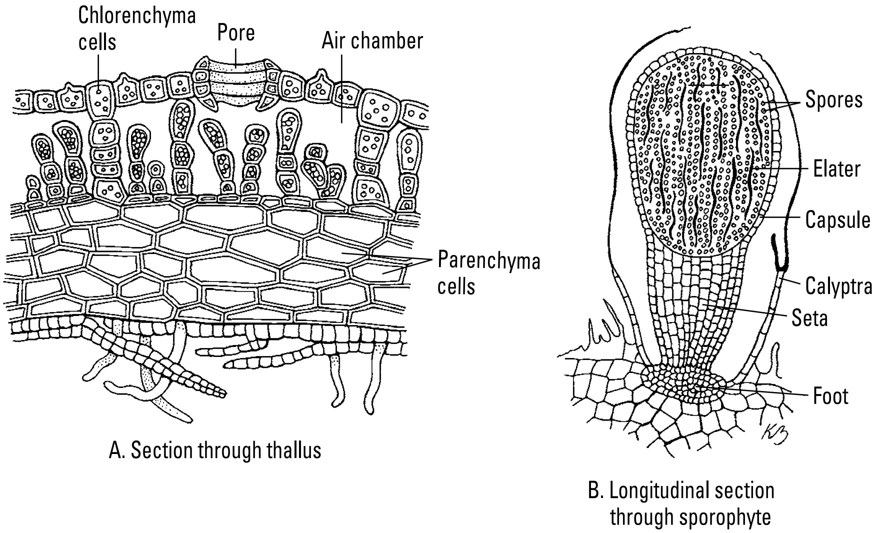

Chlorenchyma cells
Pore
Air chamber
Parenchyma cells
A. Section through thallus
Spores
Elater
Capsule
Calyptra
Seta
Foot
KB
B. Longitudinal section through sporophyte

FIGURE 14-2: Cross-section through a complex, thallose liverwort (*Marchantia*).

Some thallose liverworts, such as the liverwort *Marchantia* shown in Figure 14-2, have a fairly complex internal structure. The pores lead into airy pockets called *air chambers* that contain little stacks of photosynthetic chlorenchyma cells. Layers of nonphotosynthetic parenchyma cells form the bottom of the thallus. (For descriptions of different types of plant cells like chlorenchyma and parenchyma, check out Chapter 2.)

Life cycle of liverworts

Liverworts begin as haploid spores. When a liverwort spore lands in a moist environment, it begins to grow by mitosis, producing a filament of cells called a *protonema*. One cell, called the *apical cell*, continues to produce new cells by mitosis to form a haploid thallus, such as the ones shown in Figure 14-1a and 14-2.

Sexual reproduction occurs when the haploid thallus produces gametangia called antheridia and archegonia:

- ***Antheridia* produce sperm.** Antheridia are little chambers on the surface of the thallus that become filled with many sperm cells.

- ***Archegonia* produce eggs.** Archegonia are little vase-like structures that form on the surface of the thallus. In liverworts, each archegonium contains a single egg in the bottom of the "vase."

Some liverworts are *monoecious*, meaning they produce male and female reproductive structures on the same plant. Others are *dioecious*, producing male and female reproductive structures on separate plants.

WARNING

Because the thallus of liverworts is already haploid, sperm and eggs are produced by mitosis, not meiosis.

When water is available, the sperm use their flagella to swim to the eggs of a different liverwort plant and fertilization occurs, producing a diploid zygote. The zygote divides by mitosis to produce an embryo that develops into the diploid sporophyte. Liverwort sporophytes are small club-shaped structures that grow out of the archegonia that they were formed in.

REMEMBER

Cells within the sporophyte called *spore mother cells* divide by meiosis to produce haploid spores, completing the liverwort life cycle.

Liverworts can also reproduce asexually by *gemmae,* little groups of cells seen in cuplike structures called gemmae cups. The gemmae can be splashed out of the cup by rain drops and grow into a new plant.

Marchantia

Scientists and teachers often use the liverwort, *Marchantia*, as an example of liverwort structure and life cycle. In *Marchantia,* the antheridia and archegonia are lifted up on little stalks, producing umbrella-like structures called *gametophores* (-*phor* means to carry, and these structures will carry gametes):

- The male gametophore is called the *antheridiophore*. The top of the antheridiophore in *Marchantia* looks like a flat disk (like the ones in Figure 14-1a).
- The female gametophore is called the *archegoniophore*. The top of the archegoniophore in *Marchantia* looks like the top of a palm tree (flip back to Chapter 9 for a drawing of the *Marchantia* life cycle).

REMEMBER

Marchantia is dioecious (plants are either female or male, not both), so some plants produce only antheridiophores, whereas others produce only archegoniophores.

The sporophyte that develops after fertilization, which is drawn in Figure 14-2B, is designed to produce spores and then eject them over a wide area. The sporophyte has three main regions:

- The *foot* attaches the sporophyte to the archegoniophore.
- The *seta* is a short thick stalk that suspends the rest of the sporophyte from the archegoniophore.
- The *capsule* is the main part of the sporophyte.

The capsule contains different types of cells. The spore mother cells undergo meiosis to produce new spores. *Elaters* are long, pointed cells that change shape rapidly, helping to eject the spores over a wide area. The elaters change shape in response to changes in humidity, twisting and untwisting to help push spores out of the sporophyte. The *calyptra* is a layer of cells that protects the sporophyte until it is mature. When the sporophyte is mature, the calyptra breaks, and the capsule splits open, allowing the spores to leave the sporophyte.

Hornworts: Phylum Anthocerophyta

Hornworts are tiny horn-shaped plants, like the one drawn in Figure 14-1b, that typically grow in moist, shaded areas. In tropical rainforests, they may cover large patches of soil or grow up onto the sides of trees.

The gametophytes of hornworts (Figure 14-1b) grow as flat, slimy-looking, blue-green patches. The twisty, horn-shaped parts of the plants are the sporophytes that grow up and out of the gametophytes.

REMEMBER

A group of cells near the bottom of the sporophyte continues to divide throughout the life of the sporophyte so that the sporophyte keeps getting longer from growth at the base. This group of cells forms a *near-basal meristem*. Hornworts are the only plant group that has a meristem in this location.

Like liverworts (see previous section), the thalli of hornwort gametophytes have openings called pores that lead to chambers within the thallus. However, hornwort gametophytes have two distinct differences from liverwort gametophytes:

- The chambers within the thalli of hornworts are filled with a gelatinous substance called *mucilage,* which is why the gametophytes of the plants appear slimy.
- When you look at the cells of a hornwort under a microscope, each cell contains a single, large chloroplast rather than many chloroplasts, as is more typical in plant cells.

REMEMBER

The sporophytes of hornworts have true stomata that can open and close and probably function in gas exchange.

Mosses: Phylum Bryophyta

Although some people don't tend to notice them much, mosses are a very diverse group of plants — there are almost twice as many kinds of mosses as there are mammals.

WARNING

Lots of small, leafy green stuff gets called moss, but it's not always a true moss. The pale green, plant-like material called reindeer moss is actually a lichen, the dark red leafy Irish moss is actually a red alga, and the long, thin, pale green strings called Spanish moss that hang from trees are actually flowering plants. To tell whether something is really a moss, look for the characteristics that I describe in this section.

Mosses can be found all around the world, growing on the forest floor, along the banks of rivers and streams, and on the arctic permafrost. They're important in the environment because they help with water and nutrient control, help prevent erosion, and help insulate the permafrost.

Structure of mosses

Moss gametophytes, like the one drawn in Figure 14-1c, usually look leafier than those of other bryophytes. The leaves of mosses are usually very simple and just one cell thick, although some moss leaves have a *midrib,* a thicker area that runs down the center of the leaf.

Moss gametophytes differ from those of other bryophytes in several ways:

- Moss gametophytes have *radial symmetry,* with their leaves arranged around a central axis, whereas the gametophytes of both liverworts and hornworts are flattened and have bilateral symmetry.
- The rhizoids that anchor moss gametophytes to the ground are multicellular, whereas the rhizoids of liverworts are unicellular.
- The leaves of mosses tend to be pointier and more leafy-looking than the leaves of leafy liverworts, which are more rounded and scale-like.

REMEMBER

Although bryophytes in general don't have vascular tissue, some mosses have cells that are very similar to vessels and sieve cells (for more on these cells, flip back to Chapter 2).

Moss sporophytes look like skinny little lanterns or flags growing off the gametophyte (you can see some in Figure 14-1c). The sporophyte has several parts, which are shown in Figure 14-3:

- The sporophyte grows upward on a stalk called a *seta*.
- The *capsule* is the chamber that forms at the end of the seta.
- The little hat-like piece of tissue that covers the capsule is the *calyptra*.

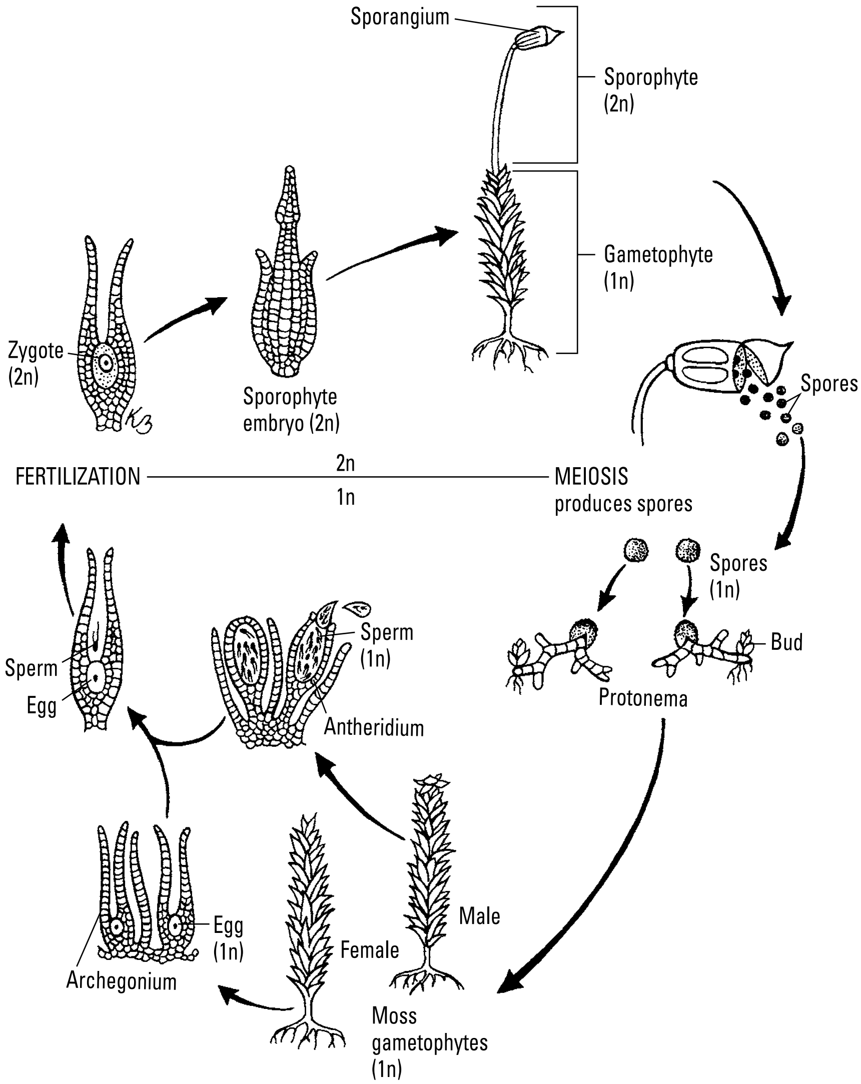

Sporangium
Sporophyte (2n)
Gametophyte (1n)
Zygote (2n)
Sporophyte embryo (2n)
Spores
FERTILIZATION
2n
1n
MEIOSIS produces spores
Spores (1n)
Bud
Protonema
Sperm (1n)
Antheridium
Sperm
Egg
Egg (1n)
Archegonium
Female
Male
Moss gametophytes (1n)

FIGURE 14-3: The life cycle of a moss.

Life cycle of mosses

Beginning with the germination of a haploid spore, the moss life cycle has the following steps (refer to Figure 14-3):

1. **The spore germinates, growing by mitosis into a filament of cells called a *protonema*.**

   As the protonema grows, it branches and forms a mat-like network.

2. **At various points along the protonema, cells divide by mitosis to produce small, leafy structures that develop rhizoids and grow into the leafy gametophytes.**

3. **At the tips of the gametophytes, or sometimes on special branches, cells differentiate to form gametangia.** A cell within each vase-shaped *archegonium* divides by mitosis to produce an egg. Cells within the saclike *antheridia* divide by mitosis to produce many sperm. Some mosses are monoecious (a single plant has male and female parts), whereas others are dioecious.

   TECHNICAL STUFF

   Sterile hairs called *paraphyses* grow between several archegonia or between several antheridia on different stems of a single plant.

4. **When water is available, the sperm swim to the egg, attracted by substances released by the archegonia.**

   The sperm fertilizes the egg, forming the diploid zygote.

5. **The zygote grows by mitosis into an embryo, which breaks down cells at the base of the archegonium and then attaches itself with a knob-like mass of cells called a *foot*.**

6. **The sporophyte grows up and out of the archegonium, taking the top of the archegonium with it, which forms the little hat-like calyptra.**

   As the sporophyte grows, it develops chloroplasts, becomes green, and starts to do photosynthesis (described in Chapter 5). However, the sporophyte continues to receive some carbohydrates, as well as water and minerals, from the gametophyte by absorbing them through its foot.

7. **The mature sporophyte, which consists of the capsule (also called a sporangium) supported on a seta, produces spores.**

   Cells within the sporangium, called *spore mother cells,* divide by meiosis to produce the haploid spores.

8. **When the spores are mature, the lid of the capsule, called the *operculum*, falls off, revealing an opening called the *peristome*.**

   Moss spores are carried away by the wind once the operculum falls off. In many mosses, the peristome is ringed with a row of triangular, membranous teeth. These teeth change shape in response to moisture, opening and closing the peristome.

FOR PEAT'S SAKE!

Peat moss is made of a moss called *Sphagnum* that has some unique and useful characteristics. If you've ever used peat moss in gardening, you probably know that it is good at holding water in the soil — but did you know that it can hold up to 25 times its own weight in water? Peat moss is so great at holding water that Native Americans used it as baby diapers. And yet, when it's dry, peat makes great fuel — people who live near peat bogs have been cutting blocks of peat and using them for fuel for centuries.

Another characteristic of *Sphagnum* is that it produces acids as it grows, making its environment acidic. The acid prevents bacteria from growing, so peat bogs are places where the decomposition of dead materials happens very slowly. Perfectly preserved bodies have been found in peat bogs, like the Tollund man that was found in the 1950s. Scientists estimated that the man lived about 400 years BC, yet when he was found, his face was clearly visible, and his clothes and hair were intact — as was the rope around his neck that was used to hang him almost 2,500 years ago!

One less creepy result of the fact that bacteria don't grow in the acid is that peat makes great bandages. And it's antimicrobial and more absorbent than cotton. In fact, when cotton bandages ran low during World War I, peat had a successful run as a replacement bandaging material.

Asexual reproduction of mosses can also occur through *fragmentation*, when pieces of moss gametophyte break off and then regrow to form new individuals.

Tracheophytes: Vascular Plants

Although bryophytes became adapted to living on the land using one set of strategies, evolution acted on another group of plants, the tracheophytes, to select for a different set of traits favorable to this strange, dry territory. Today's descendants of these tracheophyte ancestors reveal the traits that made them successful:

- **Better control of internal water concentration.** Plants developed thicker cuticles, providing better waterproofing. Stomata that could open and close to regulate gas exchange and control water loss became the norm, rather than pores like those in bryophytes that stay open all the time.
- **Development of roots to increase water and mineral uptake from the soil.** Scientists think roots evolved in ancient vascular plants from stems that grew along or just under the surface of the soil. Once these surface branches

started growing under the surface of the soil, they were exposed to different conditions than the branches above ground. Plants whose underground branches were able to absorb water had an advantage over other plants, leading to the evolution of a more root-like structure over time.

- **Internal vascular tissue for conducting water and sugar throughout the plant body.** In particular, the development of water-conducting tracheids helped change the way plants grow. Because of their strong, lignified cell walls, tracheids provide greater structure and support to plants, enabling plants to grow more erect.
- **A more erect, branched pattern of growth.** Branching let the early land plants produce multiple sporangia per plant, increasing their chances of reproductive success. And once plants started producing leaves, branching allowed plants to spread their leaves out so that they didn't shade each other, maximizing the capture of sunlight for photosynthesis.
- **The evolution of leaves, allowing better capture of light.** Small, simple leaves, called *microphylls*, evolved in a group of plants called lycophytes. Microphylls are simple leaves with a single unbranched vein of vascular tissue. In addition, larger, more complex leaves called *megaphylls* developed in almost all other vascular plants. Megaphylls have branching veins. Scientists think megaphylls evolved when leaf tissue grew around small, flat clusters of branches, joining them together in a leaf-like structure. Over time, the branches became the branching veins within the leaf.

The combination of these new traits gave plants much better control over their internal water content, increased their reproduction, and improved their ability to effectively harvest light for photosynthesis.

In this chapter, I take a look at the seedless vascular plants, which are very similar to the earliest land plants. In the next two chapters, I dive into two groups of tracheophytes that dominate many modern landscapes, the gymnosperms (Chapter 15) and the angiosperms (Chapter 16).

Seedless Vascular Plants

An important characteristic of plants that first appears in the seedless vascular plants is heterospory. *Heterosporous* plants produce two different types of spores (*hetero-* means different):

- *Megaspores* are larger and grow into female gametophytes.
- *Microspores* are smaller and grow into male gametophytes.

Within the plant kingdom, heterospory evolved many times, so scientists think it must have given plants a real advantage. Many plant groups today, including the very successful flowering plants, are heterosporous. Plants whose sporophytes make just one kind of spore are *homosporous* (*homo-* means same).

After these evolutionary innovations occurred, groups of land plants expanded and evolved into many different species, creating a burst in plant diversity between 417 and 354 million years ago (the Devonian Period) that eventually led to the development of the first forests between 354 and 290 million years ago (the Carboniferous period).

REMEMBER

Over these time periods, the relationship between the gametophyte and sporophyte generation changed, and sporophytes became the more dominant plant generation with gametophytes getting progressively smaller and more protected by the sporophyte. Botanists think that the reason sporophytes became dominant is that all the adaptations that allow plants to survive in dry environments evolved in sporophytes.

All seedless vascular plants (ferns, horsetails, club mosses) have several characteristics in common:

- The sporophyte is the dominant phase of the life cycle, but the gametophyte is independent and photosynthetic.
- The sporophyte makes and disperses spores from sporangia.
- The gametophyte makes gametes in gametangia.
- They require water for sexual reproduction so the sperm can swim to the egg.
- The sporophyte has vascular tissue, a cuticle, and stomates.

Club mosses: Phylum Lycophyta

The lycophytes that are alive today are small plants that look a lot like mosses (refer to Figure 14-1d). These looks are deceiving, however, as lycophytes are definitely not mosses.

REMEMBER

In mosses, the gametophytes are the more visible part of the life cycle, but in lycophytes, the sporophytes are more visible. Lycophyte gametophytes are very tiny and some even live underground, relying upon a symbiotic relationship with a fungus to provide them with nutrients and water.

Many lycophytes grow from rhizomes that branch *dichotomously*, periodically splitting into two forks. New shoots grow off the rhizome and may stand upright or may dangle off to the side of the rhizome.

Three groups of lycophytes exist today:

- **Lycopods,** which are often called club mosses or ground pines can be found looking a lot like little pine trees as they grow along the forest floor in temperate regions. (The drawing in Figure 14-1d is a lycopod.)
- **Spike mosses** are flatter and more moss-like in their appearance than the lycopods. Some species of the spike moss *Selaginella* are known for their ability to survive in harsh, dry conditions, such as rocky desert outcrops. Other species grow within the tropical rainforest canopy.
- **Quillworts** are spiky little plants that almost look like tufts of grass and are typically found growing in marshy areas.

Structure of lycophytes

Lycophytes have true leaves, roots, and stems that contain vascular tissue. The leaves of lycophytes are microphylls.

The sporophytes of each group of lycophyte have a unique growth form, which are compared in Table 14-1:

- **Club mosses:** The branching rhizomes of club mosses, such as those in the genus *Lycopodium,* grow along the forest floor, periodically growing little shoots that either stand up like little pine trees or dangle off the rhizomes (refer to Figure 14-1d). Most lycopods are less than a foot tall, but some tropical species grow up to five feet long.
- **Spike mosses:** The rhizomes of spike mosses, such as those in the genus *Selaginella*, are more branched than those of lycopods.
- **Quillworts:** Quillworts, such as the one drawn in Figure 14-1e, belong to the genus *Isoetes*. They grow in dense little clusters and on the surface look quite different from other lycophytes.

TABLE 14-1 A Comparison of Lycophyte Groups

Characteristic	Club mosses	Spike mosses	Quillworts
Branches	Shoots may be branched or unbranched. Shoots that do branch split evenly, making symmetrical forks in a type of branching called *isotomous branching*.	Shoots usually look flat, and their branching is typically *anisotomous* — when the shoot splits, one branch at the fork grows longer than the other.	The short, thick stems of quillworts form perennial underground corms.
Leaves	Small leaves wrap around the stems, either in a spiral or in individual rings of leaves called whorls.	Small leaves are arranged in spirals around the shoot. At the base of each leaf is a small flap of extra tissue called a *ligule* (ligule means tongue).	Longer leaves are arranged in a tight spiral around the short stem, growing up like tufts of quills. Bases of leaves have ligules
Roots	Adventitious	Adventitious roots, sometimes called *rhizophores*, look like little brown strings dangling down from the stem and then growing into the soil.	Adventitious and dichotomously branched

HERE THERE BE GIANTS

Although lycophytes today are mostly small plants, at one time, giant lycophytes ruled the Earth. During the Carboniferous period (354 to 290 million years ago), lycophyte trees over 100 feet tall grew in hot and humid swamps along with other types of plants. These giant lycophytes, such as the tree *Lepidodendron*, looked very similar to their smaller relatives, with dichotomously branching roots and shoots. The leaves fell off the upward growing trunks of the trees, leaving very distinctive diamond-shaped patterns of leaf scars. Because the scars look like scales, these trees are sometimes referred to as scale trees. Climate change at the end of the Carboniferous led to the death of the plants and caused their remains to be covered with seawater. The huge masses of plant material were buried in such a way that decomposition was very slow, allowing the carbon-containing plant material to be transformed into the coal and other fossil fuels that humans rely upon today.

Life cycles of lycophytes

Within the lycophytes, club mosses are homosporous, whereas spike mosses and quillworts are both heterosporous.

When lycophyte sporophytes are ready to make spores, they produce little bean-shaped sporangia that are tucked into the pockets, or *axils*, where the leaves meet the stem. (Check out Figure 14-4 to see a drawing of the sporangia tucked into the leaves.)

REMEMBER

Leaves that have sporangia on them are called *sporophylls* (*spor* refers to the spores, *phyll* means leaf, so sporophylls are spore-bearing leaves). In heterosporous lycophytes, leaves that bear *megasporangia* are called *megasporophylls*, whereas leaves that bear *microsporangia* are called *microsporophylls*.

In some lycophytes, the sporophylls look very similar to other leaves and are mixed in among them in zones along the stem. In others, the sporophylls are small and brown and clustered together in cone-like structures called *strobili*. You can see strobili on the club mosses in Figure 14-1d and 14-4.

Figure 14-4 shows the life cycle of the club moss, *Lycopodium*, as an example of the life cycle of homosporous lycophytes:

1. **Mature diploid sporophytes produce sporangia on sporophylls.**

   Within the sporangia, spore mother cells divide by meiosis to produce haploid spores.

2. **The spores are released into the air, and when they land in a suitable environment, they begin to grow by mitosis to produce the haploid gametophyte.**

3. **Club moss gametophytes are monoecious, so each gametophyte produces both archegonia and antheridia on its surface.**

   Cells within archegonia divide by mitosis to produce a single egg in each archegonium. Cells within antheridia divide by mitosis to produce sperm.

4. **When moisture is available, the sperm swim to the eggs and fertilize them, forming the diploid zygote.**

   The zygote divides by mitosis, producing first the embryo and then growing into the sporophyte.

Some club mosses also reproduce asexually by producing little structures called *bulbils*, in the axils of their leaves. When bulbils fall off the plant, they can grow into new sporophytes.

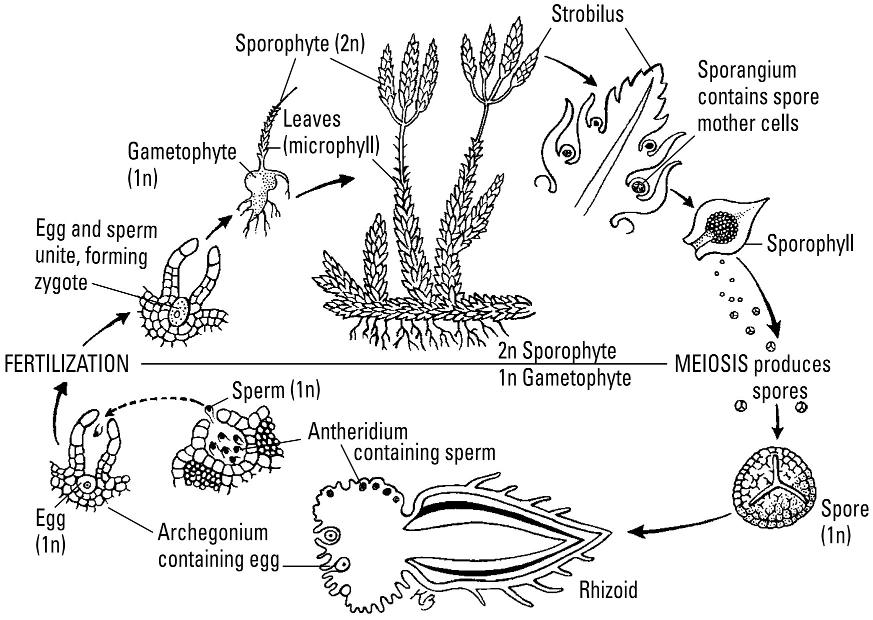

Strobilus
Sporophyte (2n)
Sporangium contains spore mother cells
Leaves (microphyll)
Gametophyte (1n)
Egg and sperm unite, forming zygote
Sporophyll
FERTILIZATION
2n Sporophyte
1n Gametophyte
MEIOSIS produces spores
Sperm (1n)
Antheridium containing sperm
Egg (1n)
Archegonium containing egg
Spore (1n)
Rhizoid

FIGURE 14-4: The life cycle of the club moss *Lycopodium*.

Although the life cycle of the heterosporous lycophytes is very similar to that of homosporous lycophytes, some key differences exist. Figure 14-5 shows the life cycle of the spike moss, *Selaginella*, as an example:

1. **Mature diploid sporophytes produce sporangia on sporophylls.**

   Megasporangia are formed on megasporophylls, whereas microsporangia are formed on microsporophylls.

2. **Within the sporangia, cells divide by meiosis to produce haploid spores.**

   Inside megasporangia, megaspore mother cells divide by meiosis to produce megaspores. Inside microsporangia, microspore mother cells divide by meiosis to produce microspores. As the names suggest, megaspores are bigger than microspores.

3. **The sporangia release the spores into the air, and when the spores find a suitable environment, they grow by mitosis into gametophytes.**

   Megaspores grow into female gametophytes that will eventually make only archegonia. Microspores grow into male gametophytes that will make only antheridia. Because the two sexes are on separate plants, heterosporous lycophytes are dioecious.

4. **Cells within the gametangia divide by mitosis to produce gametes.**

   Cells within the archegonia divide to produce eggs, whereas cells within antheridia divide to produce sperm.

5. **When moisture is available, sperm swim to the eggs and fertilize them, forming the diploid zygote.**

   The zygote divides by mitosis to produce the embryo, and eventually the mature sporophyte.

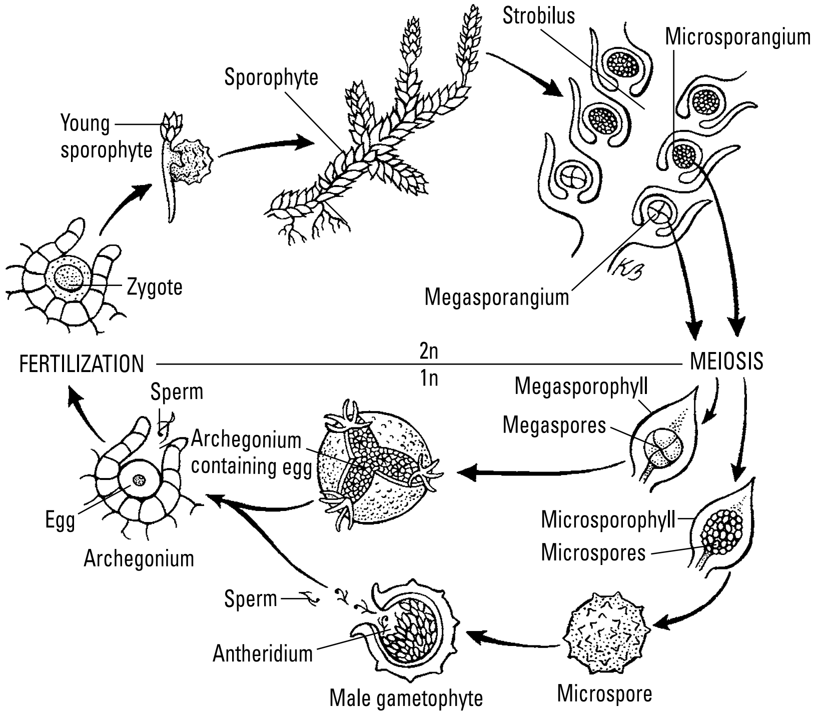

Strobilus
Microsporangium
Sporophyte
Young sporophyte
Zygote
Megasporangium
FERTILIZATION
2n
1n
MEIOSIS
Sperm
Archegonium containing egg
Megasporophyll
Megaspores
Egg
Archegonium
Microsporophyll
Microspores
Sperm
Antheridium
Male gametophyte
Microspore

FIGURE 14-5: The life cycle of the spike moss, *Selaginella.*

Ferns and (some of) their allies: Phylum Pterophyta

Scientists sometimes use the phrase *fern allies* to refer to the seedless vascular plants like the lycophytes, horsetails (see Figure 14-1f), and whisk ferns (see Figure 14-1g). Until recently, scientists considered the ferns and their allies to be four separate phyla: Lycophytes were grouped in the Lycophyta, horsetails in the Sphenophyta (or Equisetophyta), whisk ferns in the Psilophyta, and true ferns in the Pterophyta (or Pteridophyta or Polypodiophyta). Based on comparisons of their DNA sequences and other characteristics, however, scientists now feel that although the lycophytes belong in their own phylum, the other fern allies are more closely related to ferns and actually belong with them in the same clade. So, some scientists have reorganized the Pterophyta (or monilophytes) to include three groups, which are compared in Table 14-2:

- **Horsetails and scouring rushes,** which are grouped in the genus *Equisetum,* literally grow like weeds all over the world. If you've ever pulled one out of your yard, you know firsthand that they're rough and scratchy to the touch. The reason they're so scratchy is because the plants deposit silica — the same element that makes up sand — in the walls of the epidermal cells that make up the stem. The silica gives the plant a gritty feel, which hasn't gone unnoticed by people who have a long history of using these plants as tools for scouring and even sharpening objects.
- **Whisk ferns,** which are in the genus *Psilotum,* got their name from their resemblance to little whisk brooms: they have no leaves or roots, so they're just clusters of branching stems. Their unique appearance resembles that of an extinct group of early plants called *psilophytes*, and for a long time scientists thought they might be descended from that group of ancient plants. The structure of their gametophytes, however, is very similar to that of true ferns, and recent comparisons between the DNA of these two groups confirm that they are close relatives. Now scientists think that whisk ferns are descended from true ferns that evolved to stop making leaves.
- **True ferns** have relatively large, often very beautiful leaves called *fronds*, so that many people have them as ornamental plants in their homes and yards. Ferns range in size from tiny floating ferns about a half-inch in size to tall, tropical tree-ferns that can grow over 75 feet tall. If you want to take a walk in a forest that will make you feel like you've gone back to the Carboniferous Period, you can visit forests of tree ferns in Australia and New Zealand.

REMEMBER

The leaves of pterophytes are megaphylls.

REMEMBER

Most pterophytes are homosporous, producing only one type of spore, which grows into a gametophyte that produces both antheridia and archegonia.

TABLE 14-2 A Comparison of Ferns and Their Allies

Characteristic	Horsetails	Whisk ferns	True ferns
Shoots	Perennial rhizomes grow underneath the soil, putting up shoots each year. Some shoots are annual; others are perennial. The stems are ribbed. Some horsetails are *dimorphic,* producing two kinds of shoots: green vegetative shoots that aren't involved in sexual reproduction and brown fertile shoots that produce spores.	Stems branch dichotomously, forming an isotomous pattern (see this pattern in Figure 14-1g). Photosynthesis occurs in the outer cells of the stem.	Stems grow horizontally as rhizomes that periodically send up vertical leaves. Some ferns make short vertical rhizomes that produce many leaves over time, eventually becoming surrounded by old leaf bases. These stump-like structures can get quite large, especially on tree ferns.
Leaves	Tiny, but evolved from megaphylls. At the nodes where the leaves attach to the stem, they fuse together forming a solid sheath of tissue.	Absent. Little green leaf-like flaps of tissue called *enations* occur at intervals along the stem. Enations are arranged in spirals around the stem, but they lack vascular tissue.	Initially form as tightly coiled structures called *fiddleheads* (or croziers), which are basically tightly rolled up fronds. As the fronds grow, the fiddleheads unroll and the frond expands. Many fern fronds, such as the one in Figure 14-1h, are pinnately compound, divided into leaflets called *pinnae* (singular: pinna). (For more on the structure of compound leaves, see Chapter 3).
Roots	Adventitious roots grow downward from the nodes along the stem.	Absent. Whisk ferns get water through rhizomes that are partnered with mycorrhizal fungi.	Adventitious roots along the rhizome.

Figure 14-6 shows the life cycle of the horsetail *Equisetum* as an example of a pterophyte life cycle:

1. **The diploid sporophytes form cone-shaped reproductive structures called *strobili*, which support the sporangia that produce the spores.**

   In dimorphic horsetails, such as the one in Figure 14-6, the strobili form at the tips of special reproductive stems. In horsetails that aren't dimorphic, strobili are produced at the tips of photosynthetic stems. Small hexagon-shaped sporangiophores grow out sideways from the strobili, forming sporangia beneath each hexagon.

2. **Inside the sporangia, diploid spore mother cells divide by meiosis to produce haploid spores.**

The spores of horsetails are wrapped with ribbon-like *elators* that extend in response to changes in humidity, acting like wings to help the spores fly through the air.

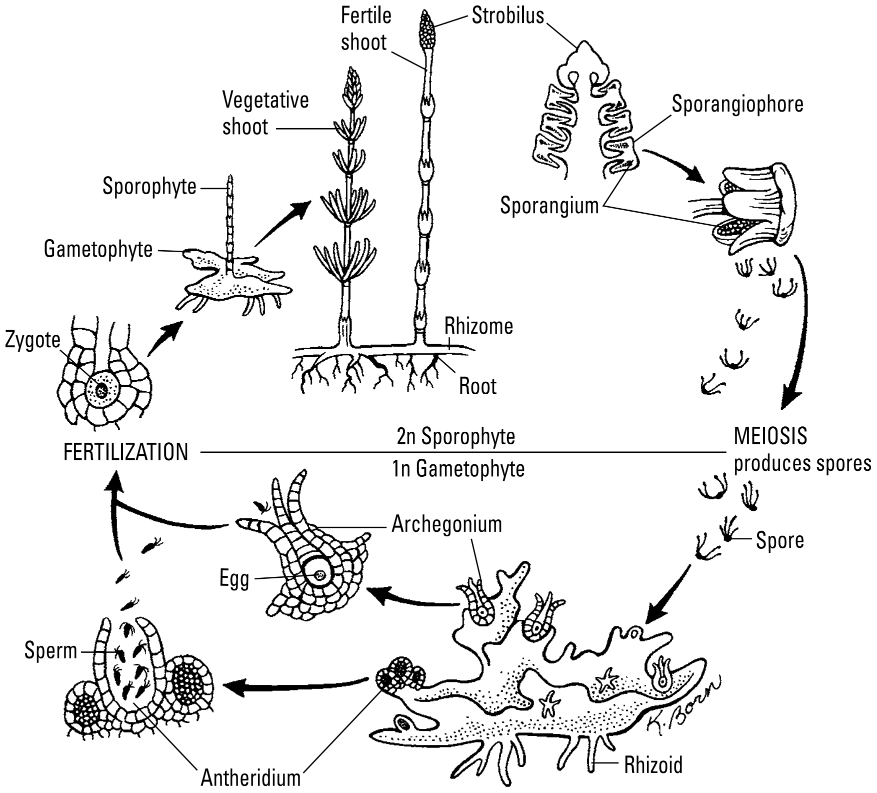

Fertile shoot
Strobilus
Vegetative shoot
Sporangiophore
Sporophyte
Sporangium
Gametophyte
Rhizome
Zygote
Root
FERTILIZATION
2n Sporophyte
1n Gametophyte
MEIOSIS produces spores
Archegonium
Spore
Egg
Sperm
Antheridium
Rhizoid
K. Born

FIGURE 14-6: Life cycle of a horsetail.

3. **When the spores land in a good environment, they grow into tiny gametophytes.**

At first, about half the gametophytes make archegonia, whereas half make antheridia:

a. Archegonia develop along the surface of half of the gametophytes, and cells inside each archegonium produce an egg by mitosis. But after a while, these female gametophytes start producing antheridia as well. Scientists call this *protogynous* reproduction, meaning the gametophytes start out strictly female but then become bisexual. Protogyny helps prevent self-fertilization.

b. Antheridia form immediately in about half the gametophytes, and cells inside the antheridia produce multiple sperm by mitosis. When water is available, changes in water pressure cause the sperm to explode out of antheridia so they can swim to the archegonia and fertilize the eggs.

4. **Fertilization forms a diploid zygote, which grows by mitosis into the embryo and then the mature sporophyte.**

Horsetails can also reproduce asexually. When the stems or rhizomes are broken, each fragment can grow into a new sporophyte.

Chapter 9 presents the fern life cycle as an example of plant life cycle with a dominant sporophyte generation. The basic life cycle of a fern is very similar to that of horsetails, with the biggest differences occurring in the sporangia and the gametophytes:

- Fern sporophytes form sporangia on the underside of the leaf.

  Often, the sporangia are clustered in little spots called sori (see Figure 14-7) that look rusty colored when mature. Different species of ferns have different patterns of sori, such as spots, stripes, and crescents. When the sporangia are immature, they may be covered by a protective flap of tissue called an *indusium*. As the sporangia mature, the indusia shrivel and peel back, exposing the sporangia.

  If you magnify a sorus, you would see the individual sporangia, which look a little like a rattle for a baby or a crested Roman helmet. The striped ridge of tissue that runs around the edge of each sporangium is called an *annulus*. The cells of the annulus have cell wall thickenings and are very sensitive to changes in moisture. When the spores are mature, the annulus snaps back, tearing open the sporangium and flinging the spores into the air.
- Fern spores germinate and grow into bisexual gametophytes that are tiny, green heart-shaped structures growing in moist environments. The gametophytes are only one cell thick in most places. Rhizoids form near the point of the heart on the lower surface and anchor the gametophyte to the ground.
- Flask-shaped archegonia develop near the notch in the heart-shaped gametophytes. Cells inside each archegonium divide by mitosis to form an egg.
- Spherical antheridia develop nearer to the rhizoids at the point of the heart. Cells inside each antheridium divide by mitosis forming many sperm. When moisture is available, sperm swim to find eggs to fertilize.

- Many ferns have ways to discourage self-fertilization. Some fern gametophytes develop their archegonia and antheridia at different times so their sperm won't fertilize their own eggs. Other fern gametophytes release hormones so that neighboring gametophytes are stimulated to produce gametes of the opposite sex.

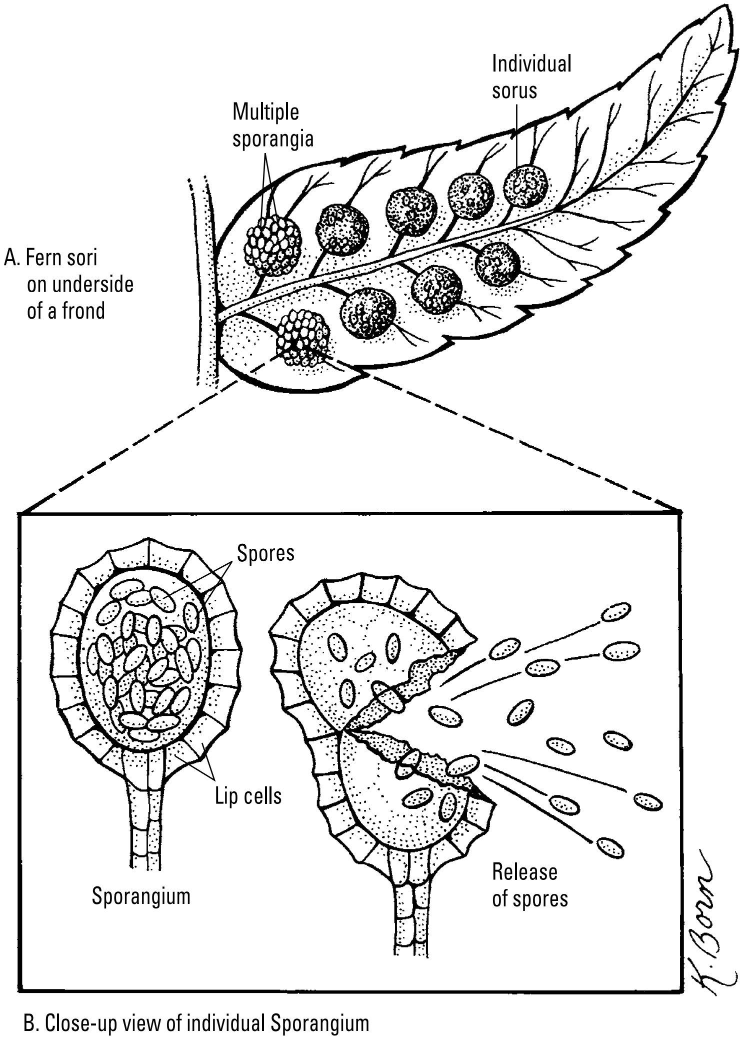

Individual sorus
Multiple sporangia
A. Fern sori on underside of a frond
Spores
Lip cells
Sporangium
Release of spores
K. Born
B. Close-up view of individual Sporangium

FIGURE 14-7: Release of spores from a fern sporangium.

IN THIS CHAPTER

- Examining reproduction in seed plants
- Exploring the diversity of gymnosperms
- Discovering the life cycle of pine

Chapter 15

Their Seeds Are Naked: Gymnosperms

Gymnosperms include very familiar plants like pine, spruce, fir, and gingko trees, as well as some plants you might never have heard of like cycads, *Gnetum*, and *Welwitschia*. Gymnosperms spread across the surface of the earth, forming the backbone of many forests. Their success is due at least in part to the evolution of seeds, which helped protect plant embryos in environments where water wasn't always available. Botanists gave this plant group the name *gymnosperm*, which means "naked seed," because gymnosperms produce their seeds on leaf-like structures that are not fully enclosed. This chapter explores the diversity of gymnosperms while also presenting the characteristics that all gymnosperms have in common.

Protecting the Embryo with Seeds

Most people probably take for granted that plants make seeds — after all, you can't eat a piece of fruit or cut open a tomato without seeing them. That's because seeds were such a good invention, that plants that make them became very successful and spread over the face of the earth.

REMEMBER

Seeds are multicellular, complex structures that protect and nourish the embryo. Seeds can survive for long periods of time in the environment, waiting for conditions to be right for the growth of the embryo. (For more on seeds, flip to Chapter 4.)

The earliest evidence for seed plants comes from fern-like plants that grew to the size of trees during the late Devonian period, over 350 million years ago. At first, botanists grouped these plants with the true ferns, but then they noticed that the fronds had seeds on them, not spores. (For details on spores and true ferns, see Chapter 14.) So, botanists put these plants into their own category, called *pteridosperms*, which means "seed ferns." Pteridosperms are classified in the plant group called gymnosperms.

REMEMBER

Gymnosperms produce seeds and pollen and have vascular tissue, but they don't make flowers or fruits.

The word gymnosperm literally means naked seeds (*gymnos* = naked, *sperma* = seed) because the seeds of gymnosperms aren't fully enclosed inside of a structure. The other group of seed-bearing plants, the flowering plants or *angiosperms*, enclose their seeds inside of fruits. Figure 15-1 compares the seed-bearing structures of gymnosperms with those of angiosperms.

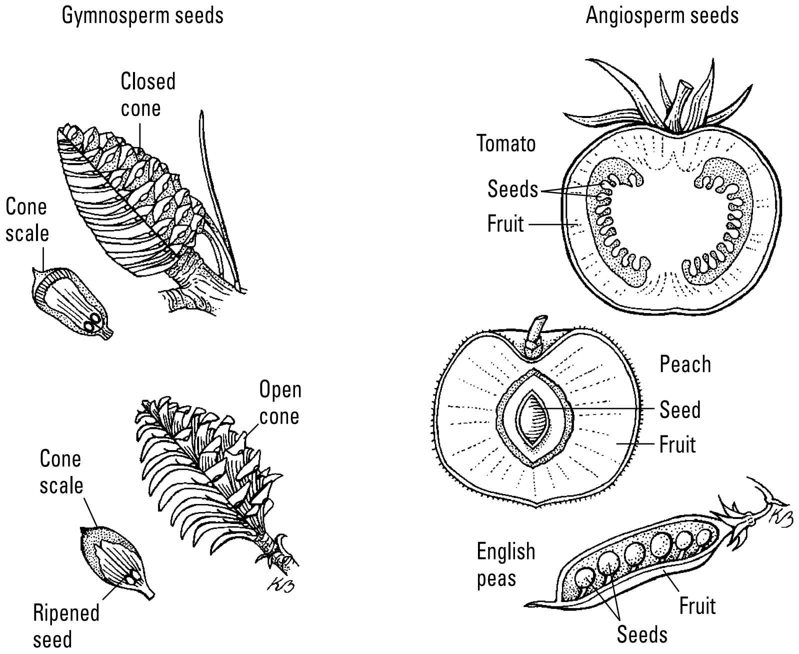

Gymnosperm seeds
Angiosperm seeds
Closed cone
Cone scale
Tomato
Seeds
Fruit
Peach
Seed
Fruit
Open cone
Cone scale
Ripened seed
English peas
Fruit
Seeds
KB
KB

FIGURE 15-1: A comparison between the seed-bearing structures of gymnosperms and angiosperms.

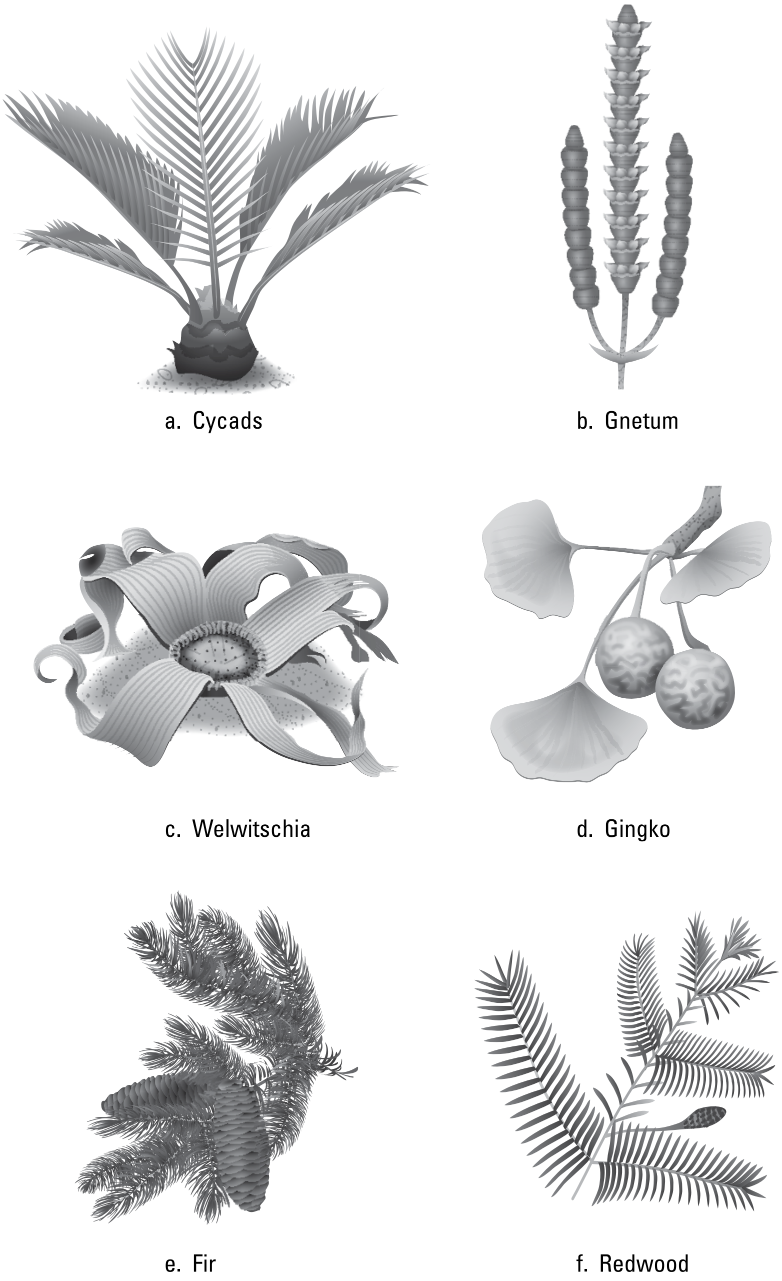
Although gymnosperms and angiosperms package their seeds differently, both groups developed similar reproductive strategies:

- **Gymnosperms and angiosperms are both *heterosporous.*** Sporophytes produce two different types of spores that give rise to unisexual gametophytes. (For a description of heterospory, see Chapter 14.)
  - Megasporangia produce megaspores that grow into female gametophytes.
  - Microsporangia produce microspores that grow into male gametophytes.
- **Gametophytes are very small and completely enclosed within ovules and pollen grains.** The outer sporophyte tissues of the ovules and pollen grains protect the fragile gametophytes inside, keeping them moist and shielding them from ultraviolet radiation.

  The male and female gametophytes are each protected by a unique structure:
  - **The male gametophyte is protected by the *pollen grain*.** Microspores develop into pollen grains that are covered with a protective coat. When pollen grains land on the female part of a seed plant, they begin to grow a long tube called a *pollen tube* that delivers sperm to the egg inside the female gametophyte
  - **The female gametophyte is protected by the *ovule*.** The megasporangium and megaspore are wrapped with layers of sporophyte tissue called *integuments,* forming a structure called an *ovule*. Inside the ovule, the female gametophyte produces one or two egg cells. After fertilization, ovules develop into seeds.

Figure 15-2 shows examples from the four groups of gymnosperms that are alive today:

- **Cycads,** like the one in Figure 15-2a, look a little bit like short palm trees because they have a crown of spiky, compound leaves that emerge from their stocky trunk.
- **Gnetophytes** are unusual plants that include *Gnetum,* shown in Figure 15-2b, and the large-leaved *Welwitschia,* shown in Figure 15-2c.
- **Ginkgos,** like the one in Figure 15-2d, may be familiar to you because they’re often planted along city streets. Their delicate, fan-shaped leaves are also often seen in Asian art.
- **Conifers** are probably very familiar to you as this group includes pines, cedars, spruces, firs (Figure 15-2e), redwoods (Figure 15-2f), and hemlocks.



a. Cycads

b. Gnetum

c. Welwitschia

d. Gingko

e. Fir

f. Redwood

FIGURE 15-2: Examples of gymnosperms a. Cycad. b. *Gnetum*. c. *Welwischia*. d. *Ginkgo*. e. Fir. f. Redwood.

Cycads: Cycadophyta

Very few cycads remain living in the wild today, but during the Jurassic period (206 to 144 million years ago), they dominated the landscape in many parts of the world. Today, cycads still grow wild in some tropical and subtropical areas and are also seen as ornamental plants. Ornamental cycads are sometimes referred to as palms, but they aren't closely related to palm trees, which are flowering plants.

Cycads have several interesting characteristics:

- **The cycad trunk is unbranched**. If the trunk is damaged, sometimes branching will occur.
- **Cycads produce some roots that grow upward and form symbiotic partnerships with blue-green bacteria.** Blue-green bacteria can capture nitrogen from the atmosphere and convert it to forms usable by plants. For more on this process, called *nitrogen fixation,* see Chapter 19.
- **Insects pollinate cycads.** Beetles are attracted to the scent and heat of the pollen. (Cycads may have evolved insect pollination 100 million years before the flowering plants!)
- **Cycads are *dioecious:* Female plants produce only female cones, and male plants produce only male cones.** Female cycad cones can be quite large, up to 2 feet long and weighing 90 pounds!
- **Cycad sperm have flagella and can swim.** Cycads and ginkgos are the only seed plants that have swimming sperm.
- **Animals disperse the large, brightly colored seeds.** In Africa, elephants eat the whole cone of some cycads and then disperse the seeds in their dung.

Unfortunately, cycads grow very slowly, and their numbers are dwindling due to habitat destruction and overharvesting by humans.

Ginkgos: Ginkgophyta

Only one species of ginkgo, *Ginkgo biloba* or the maidenhair tree, is still alive today. Fossils of ginkgo leaves date back to almost 200 million years ago, and individual trees can live 1,000 years, but the last survivors of this ancient lineage are almost extinct in the wild today. Most of the remaining ginkgos belong to populations that were cultivated for their beauty or as a food source (you can eat the inner seed after removing the outer toxic — and smelly! — part). Today, you can often see ginkgos turning a beautiful golden color in the Fall along city streets, where they are planted due to their resistance to pests and pollution.

Although ginkgos look very different from other gymnosperms, they have other characteristics like naked seeds that place them firmly in this group:

- **Ginkgo leaves are flattened and *deciduous,* with fine, dichotomously branching veins.** In autumn, the leaves turn a beautiful yellow color before they fall from the trees.
- **Like cycads, ginkgos are dioecious: Male and female parts occur on different trees.** The seeds of ginkgo have a strong, unpleasant odor, so typically only males are planted along city streets.
- **Also like cycads, ginkgos have motile sperm.** The sperm swim to the egg to achieve fertilization.
- **Gingko seeds have an outer, fleshy covering.** Although the covering has a rancid odor, the inner part of the seed has nutritious and medicinal properties. Certain cultural groups in China have a long history of cultivating ginkgos for their seeds.

Conifers: Coniferophyta (Pinophyta)

If you've ever strolled beneath the giant redwood trees of California, or walked among the shady cool trees of a forest dominated by pine, spruce, or cedar, you've experienced the beauty of conifers. Conifers are the largest and most diverse group of living gymnosperms, second only to the angiosperms in terms of distribution of seed plants around the world. Members of this group range in size from shrubby junipers to the giant redwood trees, and dominate large forests in the United States, Canada, Europe, and Asia in areas that are cold or dry.

Conifers get their name because they typically produce their seeds in woody *cones* (*conus* = cone *and ferre* = to carry), so conifers are literally cone-bearing plants. However, some types of conifers, like junipers and yews, produce unusual cones or even no seed cones at all:

- **The female cones of junipers are fleshy.** These round, bluish cones are often called *juniper berries,* but they're not berries at all.
- **Yew trees don't produce female cones.** The seeds of yew are surrounded by a red, fleshy layer called an *aril,* which gives the seeds a berry-like appearance. Not only aren't arils really berries, but their seeds are poisonous as well.

A CANCER-FIGHTING TREE

The Pacific yew tree, *Taxus brevifolia,* has saved many lives. Pacific yews grew quietly in the forests of the Pacific Northwest, and people considered them of little value next to the taller Douglas Fir and Sitka Spruce. But then, in the 1960s, the USDA went looking for anticancer drugs, starting a huge screening program that examined thousands of plants for any chemicals that were active against tumors. The bark of the Pacific yew yielded a chemical, later named *taxol,* that showed anticancer activity. Taxol stops cancer cells from multiplying and is used to treat breast and ovarian cancer, as well as Kaposi's sarcoma. For a while, taxol was in such high demand that the survival of the Pacific yew was threatened by overharvesting of its bark. Fortunately for the trees, scientists developed a synthetic version of this valuable drug that doctors still use today to fight breast cancer.

Except for differences in cones, conifers share certain characteristics:

- **Conifers have simple leaves with single veins.** Although the leaves of conifers are sometimes very small, they aren't like the rudimentary leaves of lycopods, which are called microphylls (see Chapter 14). Fossils of extinct conifers show that the ancestors of modern conifers had larger, more complex leaves called *megaphylls*, so the small leaves of modern conifers must have evolved as a reduction in size from the original megaphylls.
- **Male and female gametophytes are produced on separate male and female cones.** Unlike cycads and ginkgos, however, many conifers are monoecious, producing both male and female cones on the same plant.
- **Conifers are wind pollinated.** The wind carries pollen from male cones to the female cones. Once the pollen reaches the ovules, it grows a pollen tube and delivers sperm to the egg.
- **Wind and animal dispersal of seeds occurs.** Some wind-dispersed seeds have flattened wing-like structures that help them catch flight. Fleshy cones and structures attract animals like birds and squirrels, who eat the cones and scatter the seeds in their feces. Some pine seeds, like the pine "nuts" of the pinyon pine, are prized by people and other animals.

Pines

Pine trees belong to the largest genus of conifers, the genus *Pinus.* You can find pine trees growing all over the world, but they are native to northern temperate regions like the coniferous forests of the Northern Hemisphere. The xylem of pine trees contains tracheids, but no vessels or fibers, making it a *soft wood* tree.

Structure of pines

Pine trees often grow in cold, dry, or windy areas where protecting themselves from water loss is a serious issue. The cross-section of a pine needle in Figure 15-3 shows some features of pine needles that help them resist water loss and pest damage:

- The epidermis has a thick, waxy cuticle.
- The stomata are sunk into the surface of the leaf, helping to reduce the rate of transpiration (see Chapter 7).
- Special resin-producing cells line channels called *resin canals,* producing resin that protects the needles from fungi and insects.
- The vascular tissue in the leaf is surrounded by a waxy layer of endodermis, which helps control the movement of water and other materials into the leaf. In most other plants, endodermis is found only in the roots (see Chapter 4).

REMEMBER

A distinctive characteristic of pines is that their needle-like leaves are clustered together in bunches of between two to five needles. The needles in each bunch, or *fascicle*, fit together to form a cylindrical shape. (The single-leaf pinon pine that grows in the southwestern United States only has one needle in each "bunch.")

Life cycle of pine

All you ever really see of a pine tree (or any gymnosperm) is the sporophyte generation because the gametophyte generation is very small and enclosed within sporophyte tissue.

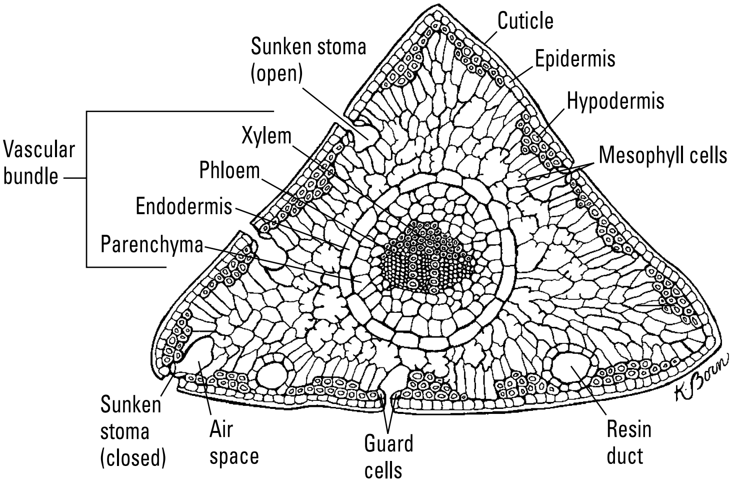

Sunken stoma
(open)
Cuticle
Epidermis
Hypodermis
Vascular bundle
Xylem
Phloem
Endodermis
Parenchyma
Mesophyll cells
Sunken stoma (closed)
Air space
Guard cells
Resin duct
K.Born

FIGURE 15-3: A cross-section of a pine needle.

Figure 15-4 illustrates the life cycle of a pine tree, showing how the sporophyte and gametophyte generations alternate:

1. **Diploid sporophyte trees produce both male and female cones.**

   Male cones, or strobili, are smaller and made up of papery scales, whereas female cones are larger and made up of woody scales.
2. **Within the cones, sporangia develop at the base of the scales.** Two microsporangia form at the base of each scale in male cones. A pair of ovules, each containing a megasporangium, develops at the base of the scales in female cones. Each pine ovule is enclosed in layers of protective sporophyte tissue called integuments.
3. **Within the sporangia, mother cells, or meiocytes, undergo meiosis to produce haploid spores** (for details on meiosis, see Chapter 9). Microspore mother cells produce four haploid microspores that develop into pollen grains. Each pollen grain consists of four cells and a pair of air sacs that stick off the pollen grain like mouse ears. The air sacs make pine pollen light and easily carried long distances by the wind. Megaspore mother cells produce four megaspores. Only one megaspore survives, growing into the multicellular female gametophyte. The female gametophyte develops slowly, sometimes taking months before it's mature. Toward the end of its development, the gametophyte produces two to six archegonia, each of which contains a single egg.
4. **Pollination occurs when the wind carries pine pollen from the male cones to the female cones.**

   Pollen enters the ovules through a small hole between the integuments called the *micropyle.* The pollen grain germinates, or begins to grow, producing a pollen tube that grows toward the female gametophyte.
5. **Fertilization occurs when a sperm cell fuses with an egg cell.**

   When the pollen tube reaches the female gametophyte, it releases two sperm cells. One sperm cell fertilizes the egg; the other breaks down.
6. **After fertilization, the diploid embryo develops, and the ovule matures into a seed.**

   The embryo, which represents a new sporophyte generation, is protected and nourished by gametophyte tissue inside the seed. The integuments that surrounded the ovule harden and become the seed coat. It takes 15 months from the time of fertilization for the seed to fully mature!

WARNING

Some of the details given above for the pine life cycle aren't always true of other conifers such as yews, redwoods, cypress, cedars, and firs. For example, only about half of the conifers have air sacs on their pollen grains, and pines are known for their particularly long seed development times.

TECHNICAL STUFF

The pine seed contains tissue from three different generations: the seed coat that developed from the integuments of the parent sporophyte, the nutritive tissue that was part of the female gametophyte, and the embryo that represents the new sporophyte generation.

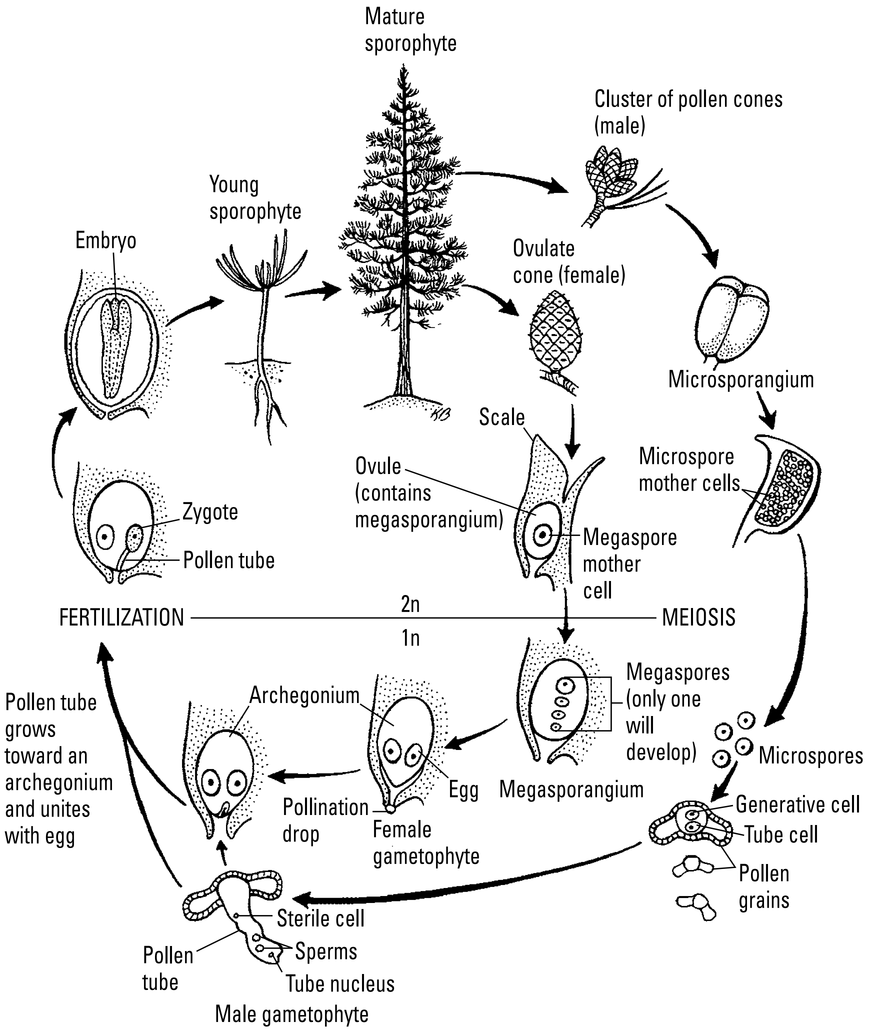

Mature sporophyte
Cluster of pollen cones (male)
Young sporophyte
Embryo
Ovulate cone (female)
Microsporangium
Scale
Microspore mother cells
Ovule (contains megasporangium)
Megaspore mother cell
Zygote
Pollen tube
FERTILIZATION
2n
1n
MEIOSIS
Megaspores (only one will develop)
Microspores
Archegonium
Pollen tube grows toward an archegonium and unites with egg
Egg
Megasporangium
Pollination drop
Female gametophyte
Generative cell
Tube cell
Pollen grains
Sterile cell
Sperms
Pollen tube
Tube nucleus
Male gametophyte

FIGURE 15-4: Life cycle of pine.

Gnetophytes: Gnetophyta

Of all the gymnosperms, botanists believe that gnetophytes are most closely related to the flowering plants. The relationship between gnetophytes and angiosperms is supported by comparisons of DNA sequences and by some structural characteristics, such as the presence of xylem vessels.

Like the cycads and ginkgos, gnetophytes were much more diverse in the distant past — today just three groups of gnetophytes remain:

- The genus *Gnetum* is the most common member of a group of broadleaved tropical plants, many of which are vines. The leaves of these plants have branching veins very similar to those of the flowering plants. *Gnetum* produces pollen and seeds in bisexual cones.
- *Ephedra,* also called Mormon tea or by its Chinese name *ma huang,* are brushy shrubs that grow in desert areas. The plants produce two or three tiny leaves at each node along the stem, but the leaves turn brown quickly and fall off, giving the plant a jointed stick-like appearance that explains why it's also sometimes called a *joint fir.* The stems of these plants are green and photosynthetic. *Ephedra* is well-known in medical circles because it produces *ephedrine,* which is a powerful decongestant.
- *Welwitschia* is the strangest of the gnetophytes. Each plant produces two large, strap-like leaves that grow continuously throughout the life of the plant. The leaf meristems are located at the base of each leaf, near the large cup that forms in the center of the plant. So, although the leaves may get split and tattered at their tips, they continue to grow from the base. *Welwitchia* is dioecious, so some plants produce female cones, whereas others produce male cones. The cones are produced around the rim of the central cup. (For more on *Welwitchia*, check out Chapter 21.)

IN THIS CHAPTER

- Examining the evolution of flowering plants
- Digging into flowering plant diversity
- Checking out pollination strategies

Chapter 16

Say It with Flowers: Angiosperms

You don't have to look very far to see the importance of flowering plants to humans — they're everywhere all around us — in gardens, art, music, and literature. We give them to each other to celebrate special occasions, show our love, and mourn for those we've lost. Flowering plants are the most abundant group of plants on planet Earth, providing food, clothing, and building materials to people, as well as being the source of homes and food for many other species. And beyond what flowering plants do for people, they're fascinating and beautiful to look at. This chapter discusses the main characteristics of flowering plants, explores the mystery of their origins, and gives you an introduction to their incredible diversity.

Delving into Flowering Plants: Anthophyta

Flowering plants are intimately woven into your daily life. Even if you haven't stopped to smell the roses today or given any as a gift, you've almost certainly eaten food, worn clothing, and used objects that came from flowering plants.

REMEMBER

Flowering plants, called *angiosperms*, are the most abundant and diverse group of plants on planet Earth. Figure 16-1 gives you just a peek into the diversity of plants found in this group.

Searching for the origin of the angiosperms

The angiosperms came blazing into the fossil record of the Cretaceous period (144 to 65 million years ago), with so many diverse groups suddenly appearing that the evolutionary origin of the angiosperms has been a puzzle to botanists ever since Charles Darwin called it an "abominable mystery."

The origin of angiosperms puzzles botanists for two reasons:

- Botanists think the ancestors of angiosperms and gymnosperms diverged from each other back in the Paleozoic (about 305 million years ago).
- Fossils that look like modern angiosperms don't appear until the Cretaceous Period — leaving a gap of over 100 million years.

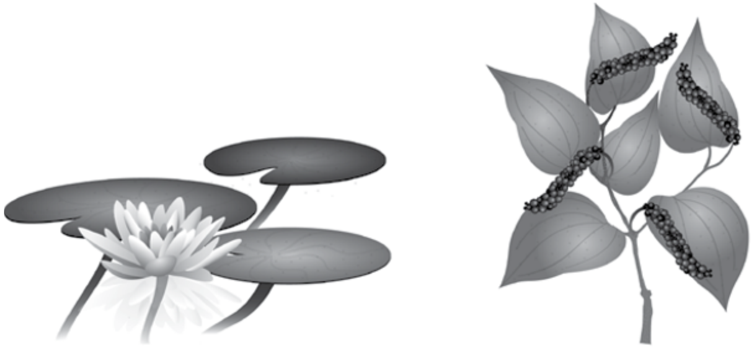
The changes that occurred in the angiosperm lineage during all that time are largely still a mystery to botanists. Some botanists propose early angiosperm evolution must have occurred in places where fossils weren't well preserved. Others think the fossil record is fairly accurate, and angiosperms just became wildly successful very suddenly. Botanists continue to try to answer this question both by studying living angiosperms and by continuing to study the fossil record.

Comparing DNA for clues

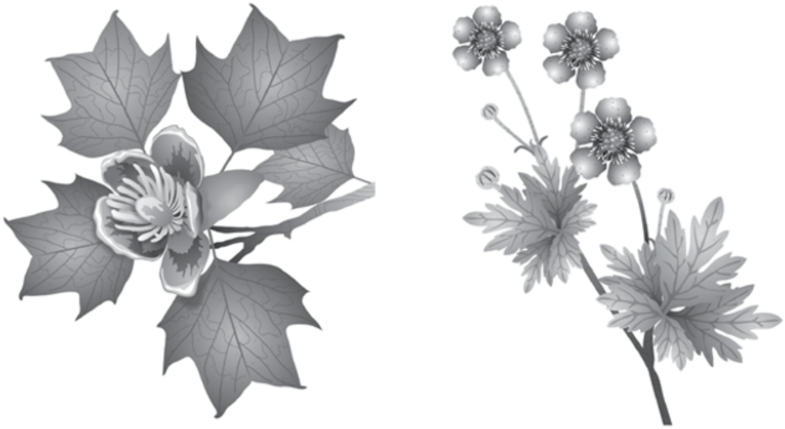
Fossils aren't the only way to explore the past anymore. Now that scientists can read the DNA of organisms, they can compare the genes of living organisms and use the information to build family trees, called phylogenies, of life on Earth. (Check out Chapter 12 for more on phylogenetic trees.) By grouping together organisms that are the most similar, scientists essentially work backwards down along the trunk of the tree to figure out which living organisms are most closely related to the ancestors at the base of the tree. This helps botanists build a picture of what those earliest angiosperms may have been like.

Based on recent comparisons of the DNA of angiosperms, taken from both living plants and from dried herbarium specimens, botanists have created the following hypothesis for the evolution of angiosperms:

- Modern angiosperms that are descendants of the earliest angiosperms form several branches at the base of the angiosperm tree, and so are called *basal angiosperms*. These plants, which botanists think may be similar to the earliest angiosperms, include a shrub called *Amborella*, water lilies (*Nymphaea*, see Figure 16-1a), and star anise (*Illicium*).



a. Water lily b. Pepper



c. Tulip tree d. Buttercup

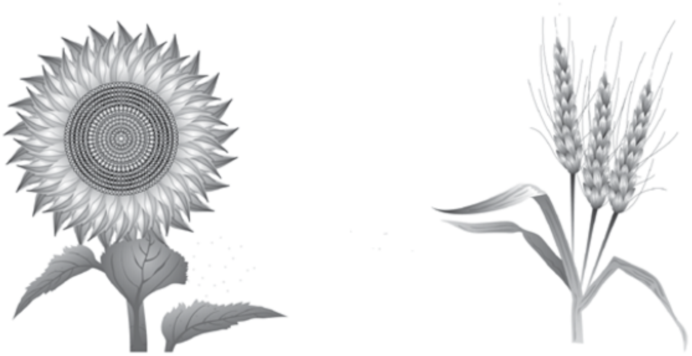


FIGURE 16-1: Angiosperm diversity.

e. Sunflower f. Wheat

- After the evolution of the basal angiosperms, more groups of angiosperms appeared. including the magnoliids, the eudicots, and the monocots, as well as a few more isolated groups that have few species.:
  - The *magnoliids* include magnolias (*Magnolia*, see Figure 16-2), tulip trees (*Liriodendron*, see Figure 16-1c), and black pepper (*Piper,* see Figure 16-1b).
  - The eudicots include buttercups (see Figure 16-1d), sunflowers (see Figure 16-1e), and maple trees, as well as a huge variety of other angiosperms, like roses, mustards, birches, and peas.
  - The monocots include grasses (see Figure 16-1f), lilies, and palms. (For a comparison of dicot and monocot characteristics, head to Chapters 3 and 4.)

WARNING

For a long time, botanists thought that the flowers of *Magnolia*, such as that in Figure 16-2, represented the earliest angiosperm flowers. Recent evidence contradicts this view, although magnolia flowers have characteristics, such as unfused parts, that are seen in early angiosperm flowers, whereas orchid flowers have many fused parts, a trait that's typically seen in newer angiosperm lineages.

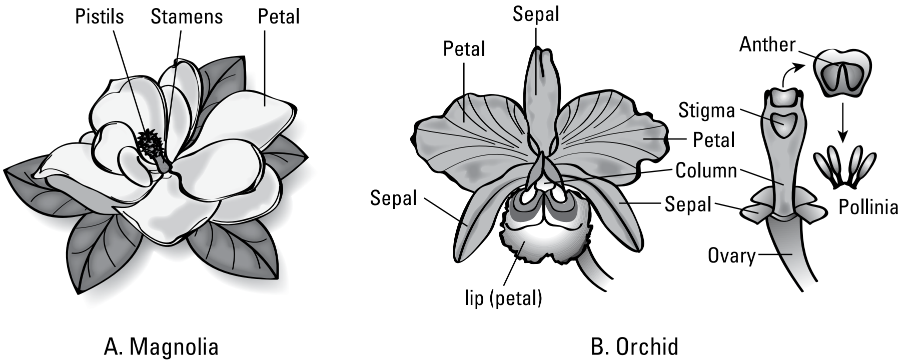


FIGURE 16-2: Primitive versus advanced characteristics in angiosperms.

Discovering the unique characteristics of angiosperms

Despite the mystery surrounding their origins, one thing is clear: Angiosperms became incredibly successful, perhaps because they combined the advantages of seeds with the evolutionary innovations of flowers and fruits. (Angiosperms were so successful, in fact, that the animal groups that evolved to use them for food or shelter also show explosive growth at the same time in the fossil record.)

Angiosperms and gymnosperms are closely related, and they have many characteristics in common (see Chapter 15). However, angiosperms also have many unique traits that unite them into the phylum Anthophyta (also called Magnoliophyta and Angiospermae):

- **Ovules enclosed in carpels:** Over time, carpels became modified to have the three parts now seen in modern flowers: the ovary, style, and stigma (see Chapter 4).
- **Pollen germinates on the stigma, rather than directly on the ovule as it does in gymnosperms:** In order for fertilization to happen, the pollen tube must grow down through the style and deliver sperm to the ovules inside the ovary. By putting some distance between the pollen and the ovules, angiosperms gained more control over fertilization. For example, in some species, if pollen from the same plant lands on the stigma it won't germinate at all, which prevents self-pollination. By making sure that fertilization comes from a separate individual, these plants increase genetic diversity in their offspring.
- **Smaller gametophytes:** Just as in gymnosperms, the gametophyte generation of angiosperms is very small and completely enclosed and protected by sporophyte tissue. But in angiosperms, gametophytes are even smaller.
  - Female gametophytes, called megagametophytes or the *embryo sac,* are made of just seven cells and eight nuclei. (One cell has two nuclei.)
  - Male gametophytes, called microgametophytes or pollen, are made of just three cells: one tube cell and two sperm cells. The male gametophyte, with a germinating pollen tube, is shown in Figure 16-3.
- **Development of endosperm to support the embryo:** Angiosperms have a unique type of fertilization called *double fertilization*.
  - One sperm cell fertilizes the egg to produce the embryo.
  - One sperm cell fertilizes two nuclei called *polar nuclei,* to produce the *endosperm*. Endosperm contains three sets of chromosomes, one from each polar nucleus and one from the sperm cell, so it is *triploid*.

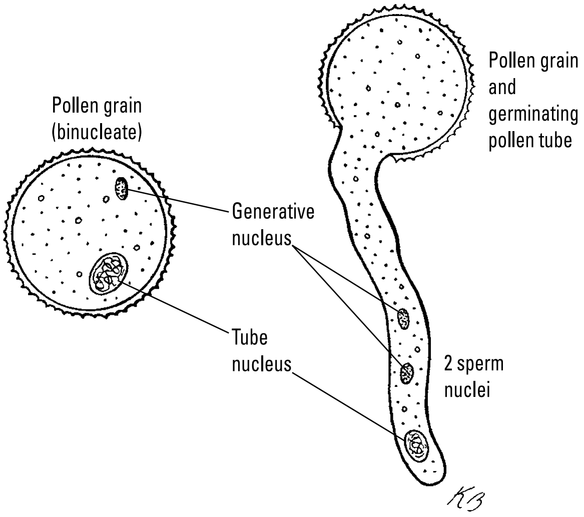


FIGURE 16-3: Growth of a pollen tube.

Looking at the life cycle of angiosperms

As in gymnosperms, the sporophyte is the dominant generation in angiosperms. Figure 16-4 illustrates the life cycle of angiosperms in a plant that has both male and female parts in the flower:

1. **The male gametophyte develops inside the anther of the flower.**

   Microspore mother cells (*microsporocytes*) inside the anther divide by meiosis to produce haploid microspores. Then the microspores divide by mitosis to produce the male gametophyte inside the pollen grain. Initially, the male gametophyte consists of two cells: the *tube cell* and the *generative cell*. The tube cell produces the pollen tube. The generative cell will divide again to produce two sperm cells.

2. **The female gametophyte develops inside the ovule of the flower.**

   The megaspore mother cells (*megasporocytes*) inside the ovule divide by meiosis to produce four haploid megaspores. Three megaspores break down, and then the surviving megaspore divides by mitosis to produce the female gametophyte, which is also called the embryo sac.

3. **Pollination occurs when pollen lands on the stigma.**

   The pollen tube grows down through the style and then through the micropyle of the ovule, delivering sperm cells to the female gametophyte.

4. **Double fertilization occurs.**

   One sperm cell fertilizes the egg, forming the diploid zygote. The other sperm cell combines with the two polar nuclei, forming the triploid endosperm. The endosperm provides food to the developing embryo.

5. **The ovule develops into a seed, and the ovary becomes a fruit.**

   The zygote divides by mitosis into a multicellular embryo that has one or two cotyledons. In some dicots, the cotyledons act as food reserves for the embryo after the endosperm has been used up; in other dicots, the endosperm is still present in the mature seed.

6. **When environmental conditions are right, the seed germinates and begins to grow.**

   The embryo develops into a new sporophyte.

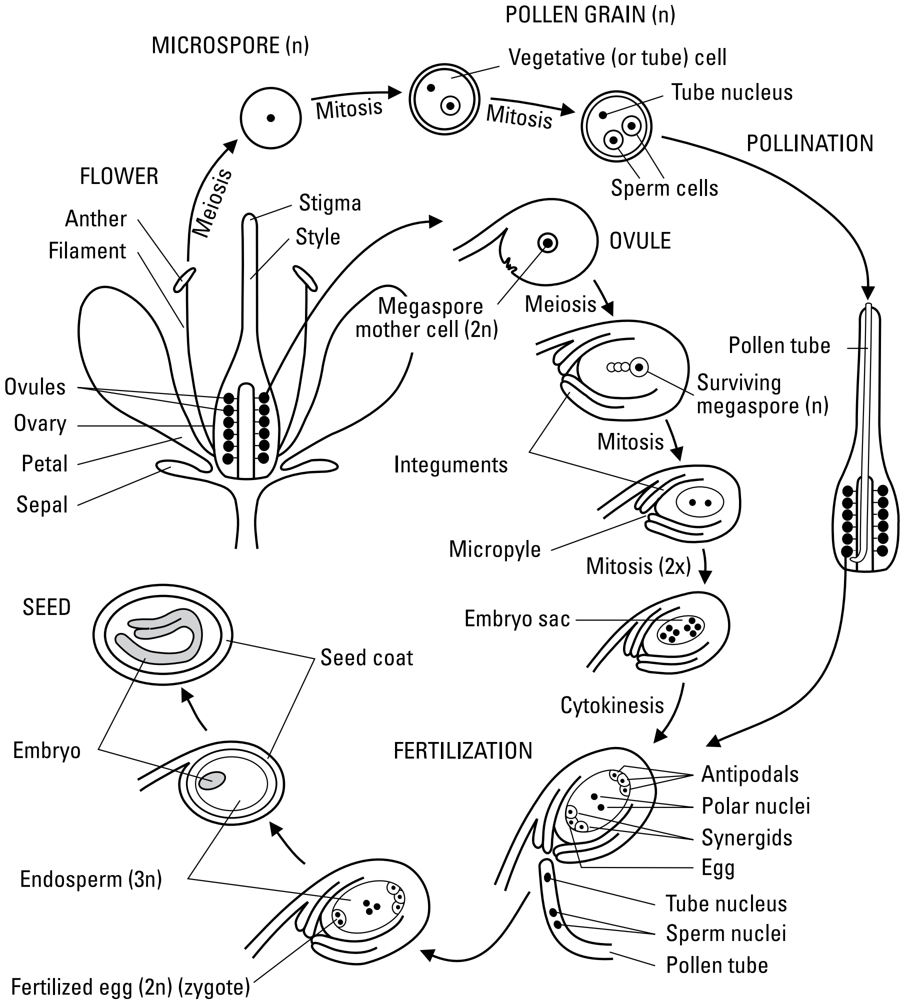

POLLEN GRAIN (n)
MICROSPORE (n)
Vegetative (or tube) cell
Mitosis
Mitosis
Tube nucleus
POLLINATION
Sperm cells
FLOWER
Meiosis
Anther
Filament
Stigma
Style
OVULE
Megaspore mother cell (2n)
Meiosis
Pollen tube
Surviving megaspore (n)
Ovules
Ovary
Petal
Sepal
Integuments
Mitosis
Micropyle
Mitosis (2x)
SEED
Embryo sac
Seed coat
Cytokinesis
Embryo
FERTILIZATION
Antipodals
Polar nuclei
Synergids
Egg
Endosperm (3n)
Tube nucleus
Sperm nuclei
Pollen tube
Fertilized egg (2n) (zygote)

FIGURE 16-4: The life cycle of angiosperms.

Exploring Angiosperm Diversity

More than 250,000 species of angiosperms populate the landscape today. Although all angiosperms make flowers, the appearance of the flowers range from flowers completely lacking petals, such as those of grasses (see Figure 16-1f), to showy flowers with lots of parts, such as those of water lilies (see Figure 16-1a).

Basal angiosperms

The oldest groups of angiosperms represent a very small percentage of the total species that exist today, but they're important because they provide clues to what the earliest angiosperms looked like.

REMEMBER

Early angiosperm flowers, such as those of the basal angiosperms and magnoliids, have radial symmetry. When something is radially symmetrical, you can imagine cutting it into slices like you'd cut a pie, and the slices all look the same. For example, bicycles wheels are radially symmetrical. More recently evolved angiosperms, such as eudicots and monocots, often have flowers with bilateral symmetry. When something is bilaterally symmetrical, its two halves mirror each other. So, if you imagine cutting it down the middle, the two halves look the same. For example, your body is bilaterally symmetrical. Botanists call flowers that are radially symmetrical *actinomorphic,* or regular, and flowers that are bilaterally symmetrical *zygomorphic,* or irregular.

Flowers of the basal angiosperms are typically bisexual with lots of separate parts that are spirally arranged. The flowers show radial symmetry and are typically insect-pollinated. Their pollen grains have one opening through which the pollen tube can grow. Some basal angiosperms don't make vessels in their xylem.

Magnoliids

Magnoliids make up about 2 percent of angiosperms. Some magnoliids that may be familiar to you are magnolias (see Figure 16-2) and tulip trees (see Figure 16-1c).

REMEMBER

The flowers of magnoliids have several characteristics in common with those of the basal angiosperms, such as making numerous, separate parts that are spirally arranged. Some magnoliids also make leaf-like stamens and unsealed carpels. Their pollen grains have one opening.

True dicots

True dicots are the largest group of angiosperms, containing about 75 percent of all angiosperm species. True dicots include familiar garden plants beans, cucumbers, and broccoli; wildflowers, such as poppies, asters, and geraniums; important ornamental and food-producing plants, such as apples and cherries; and trees, such as oak and maple.

TIP

Botanists call this group the *eudicots*, which means true dicots, to separate them from the magnoliids. The magnoliids also have two cotyledons, but evolved separately from the eudicots. Although these two groups are separate in terms of evolution, many classical taxonomic schemes place them together in one class (Magnoliopsida or Dicotyledones).

There are so many different kinds of eudicots, in fact, that it would take a whole book just to describe them all. As a way of at least introducing you to this group, I present a few examples of various eudicot flowers. Also, don't forget that for the general vegetative and reproductive characteristics of dicots, you can refer to Chapters 3 and 4.

Figure 16-1d shows a flower from the buttercup family. This family, the Ranunculaceae, belongs to one of the earliest eudicot groups to evolve. The flowers have many separate male and female parts, just like those of the basal angiosperms and the magnoliids. One difference, however, is that the pollen grains of buttercups have three openings through which the pollen tube can emerge, rather than just one opening.

REMEMBER

True dicot pollen has three openings for the pollen to grow out, which is one of the characteristics that separates this group from the other groups of angiosperms.

Figure 16-5 shows a flower from the legume family, or Fabaceae, which botanists used to call the Leguminosae. The legume family is the third largest flowering plant family and has huge importance to human agriculture. Peas, green beans, and peanuts all belong to this family.

Some familiar legumes, such as the one shown in Figure 16-5, make a special type of flower that's sometimes called a *flag flower* (or papilinioid flower):

- Flag flowers are bisexual flowers with five fused sepals and five petals that have unique shapes:
    - One petal, called the banner or standard sticks up above the flower.
    - Two petals, called the wings, stick out to the sides.
    - Two petals are fused together to form a cupped structure, called the keel, at the bottom of the flower.
- Most legume flowers have ten stamens, nine of which are fused together and one of which is separate.

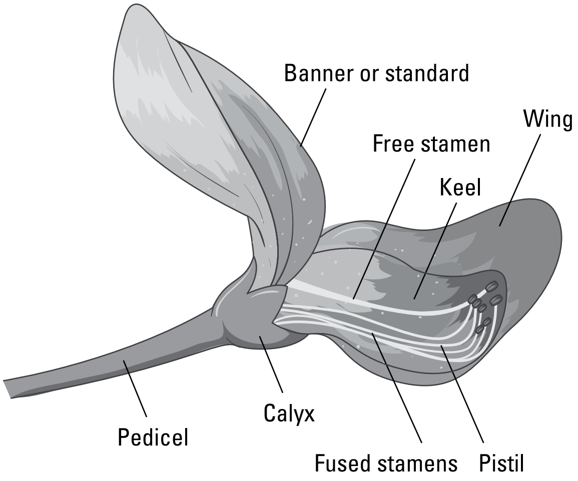

Banner or standard
Wing
Free stamen
Keel
Pedicel
Calyx
Fused stamens
Pistil

FIGURE 16-5: Parts of a legume flower. The five petals of this flower have unique shapes, forming a flag flower.

Figure 16-6 shows a flower from the spurge family, or Euphorbiaceae. This family is one of the largest plant families and is known for plants that produce milky sap. Many spurges are succulent, resembling cacti.

Spurge flowers lack petals and many lack sepals as well, so that flowers may consist of just male or female parts such as the one in Figure 16-6. The flowers are unisexual.

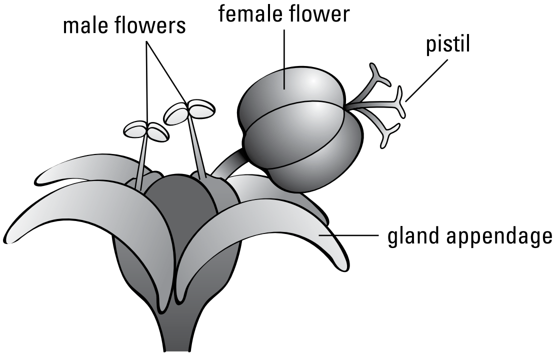

male flowers
female flower
pistil
gland appendage

FIGURE 16-6: Parts of a spurge flower.

Tomatoes, potatoes, chile peppers, tobacco, jimson weed, and deadly nightshade all belong to the nightshade family, or Solanaceae. The family is famous for producing chemicals called alkaloids, many of which are extremely toxic. Flowers in this family often have fused petals that form a tube with a pleated appearance. The flowers also have stamens that are partially fused to the petals. Botanists refer to stamens like these as *epipetalous*, because *epi-* means *upon*, and the stamens are upon the petals.

The sunflower family, or Asteraceae, is the largest dicot family and includes many beautiful wildflowers such as sunflowers such as the one in Figure 16-1(e), and the familiar guest of lawns and gardens, the dandelion.

The flowers of the Asteraceae form a characteristic inflorescence called a head that looks like a single flower but is actually a composite of many flowers. The part of the head that looks like petals is made up of *ray flowers.* The center of the head is made up of *disk flowers.* Each disk flower has a tubular corolla. The stamens in this family form a tube around the style, with the anthers fused together. The heads of asters may have both ray and disk flowers, like in a sunflower, just disk flowers like in thistles, or just ray flowers, like in dandelions.

Monocots

Monocots make up about 23 percent of angiosperm species. Monocots include orchids, grasses, lilies, and palm trees.

For the general vegetative and reproductive characteristics of monocots, see Chapters 3 and 4. As examples of the diversity of this group, this section presents a few monocots that have very different looking flowers.

Members of the lily family, or Liliaceae, such as the flower in Figure 16-7, have classic monocot flowers with parts in threes. Members of this family and their close relatives typically have bisexual flowers with parts in multiples of three, such as six tepals (or three sepals and three petals), six stamens, and three fused carpels. The flowers show radial symmetry and produce pollen grains with one opening. Most members of this family are perennial herbs.

WARNING

Although monocot pollen has one opening, the structure of monocot pollen is different from the pollen of the basal angiosperms and magnoliids. Based on all their characteristics, including DNA comparisons, botanists think that monocots are a unique group of angiosperms that evolved later than the basal angiosperm group and is most closely related to the eudicots and magnoliids.

Orchids are some of the most exotic and beautiful flowers in the world. They're prized as ornamentals and also include some important agricultural plants, like vanilla. Members of this family, such as the flower in Figure 16-2, often have very unusual looking flowers, some of which mimic insects or bats. (For more details, see the next section on pollination ecology).

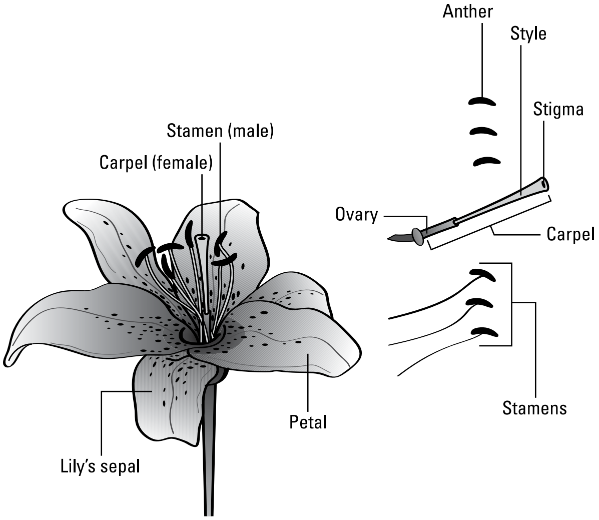


FIGURE 16-7: Parts of a lily flower.

Orchid flowers are typically bisexual and bilaterally symmetrical, having three sepals and three petals, with one petal modified to form a landing platform for pollinators called a *labellum.* The flowers have one or two stamens and three fused carpels. The style, stamens, and stigma are also fused together to form a central column. The pollen grains have one opening are packaged into bags called *pollinia*. Orchid seeds are tiny and lack endosperm, and they can't even germinate unless they establish a symbiotic relationship with a mycorrhizal fungus.

Many orchids are epiphytic, growing on other plants. These orchids have swollen stems called *pseudobulbs* that help store water. They also have aerial roots covered with a layered epidermis called *velamen* that helps orchids collect water and minerals from the air.

Grass flowers are usually bisexual, with zero to three tepals. Tepals are sometimes modified to scale-like structures called *lodicules* at the base of the flower. The flowers have one, two, three or six stamens, and two to three carpels fused to make one pistil. The stigma is feathery, which is useful for catching airborne pollen.

The flowers are arranged in inflorescences called *spikelets*. Each flower sits in a pair of bracts, forming a *floret*. Each floret has a lower bract called a *lemma* and an upper bract called a *palea*. One or more florets grow above two bracts called *glumes,* forming the spikelet. The main axis of the spikelet that supports the florets is the *rachilla.*

Grass leaves occur in pairs in a two-ranked arrangement: The leaves alternate and have bases that wrap around the stem so that one leaf sits slightly above the other, emerging from its open sheath. A small flap of tissue called a ligule is attached to the leaf base, where it wraps around the stem.

Thinking about Pollination Ecology

One really cool thing about angiosperms is their interactions with animals. Angiosperms control animal behaviors, getting animals to bring them pollen by attracting them with certain colors and scents and offering them rewards of food. Angiosperms also get animals to disperse their fruits, seeds, and pollen by hitching a ride on their surfaces or offering them food. But wait a minute! Perhaps it's the other way around. Maybe the animals caused the angiosperms to serve the needs of the animals by dispersing pollen and seeds. Actually, scientists think it's a bit of both — that over time, the interactions between angiosperms and animals have affected the evolution of both groups.

REMEMBER

Coevolution is when two species affect the evolution of each other, so that both groups develop traits in response to the other. (For more details on evolution and how it works, see Chapter 11.) The coevolution of angiosperms and animals is part of the reason that angiosperms are so colorful and diverse. Flowers have changed over time to be attractive to certain animals, and not others. And animals have changed to efficiently gather resources, such as nectar from flowers.

You can make a pretty good guess about which plants are getting animals to work for them, by checking the plants for animal signals and rewards. Plants that lure animal pollinators typically have bright colors and intriguing scents and may offer a food reward such as nectar. Wind-pollinated plants, by contrast, may seem drab — no showy flowers, just reproductive parts hanging in the breeze, but if you have allergies, you may definitely notice the wind-pollinated plants because they tend to put out lots of pollen to make sure that they get the job done!

Plants that lure animals to disperse their fruits and seeds typically fall into one of two camps: those that offer juicy rewards like fleshy fruits, and those that sneakily hitch a ride on fur, hair, or feathers, using sticky barbs and spines. Plants that rely upon the wind to do the work make light, dry seeds and fruits that can float easily on the breeze. Many of them make wings or parachutes to help carry their reproductive structures on the breeze.

REMEMBER

By attracting animal pollinators, plants help make sure that they receive pollen from diverse mates, helping to increase genetic diversity. When an animal visits a flower, pollen is transferred to its body. Then, when the animals move to a different individual, some of the pollen from the previous flower rubs off, achieving *cross-pollination.*

Flowers and their pollinators have evolved very fine-tuned relationships:

- **Flowers that are pollinated by insects provide a food reward and have colors, scents, and shapes that attract certain insects:**

  - *Bee-pollinated flowers are usually bright blue or yellow because those are colors that bees see well, and they have a sweet fragrance to attract the bees.* Bees can also see something you can't — ultraviolet light — so bee-pollinated flowers look different to bees than they do to you.
  - *Fly-pollinated flowers tend to be dark red or brown colors and smell like rotten meat or animal waste.* (I personally have smelled fly-pollinated flowers that reminded me of urine.) Because of their rotten meat appearance and smell, some fly-pollinated flowers are called *carrion flowers*. Flies are attracted to the flowers to lay their eggs and in the process, pick up pollen for dispersal.
  - *Beetle-pollinated flowers are usually white or dull colors and have strong fruity or spicy odors.* The flowers provide the beetles with food, either as pollen or by making special food-storage cells on the petals.
  - *Some wasp-pollinated orchids look like certain female wasps and trick the male wasps into attempting to mate with them!* For more on this strange occurrence, see Chapter 21.
  - *Butterfly-pollinated flowers are usually brightly-colored, tube-shaped flowers that have a sweet smell.* Butterflies have long, rolled-up tongues, so they can probe deeply into tube-shaped flowers for their nectar reward. Butterflies can see the color red so many butterfly-pollinated flowers are red, orange, or yellow.
  - *Moth-pollinated flowers are similar in shape and smell to butterfly-pollinated flowers, but are usually white.* That's because moth-pollinated flowers are typically open at night when moths are more active.
- **Bird-pollinated flowers are usually bright red or yellow but don't have much scent.** That's because birds have great vision, but a poor sense of smell. Bird-pollinated flowers may be tubular like butterfly flowers because bird beaks can probe deeply into flowers. Birds, especially hummingbirds, use up a lot of energy while visiting flowers, so the flowers provide lots of nectar to make sure the birds keep coming back for more.
- **Bat-pollinated flowers tend to be single large flowers or clusters of many flowers that are white or light-colored and have a sweet fruity smell or a musty, bat-like smell**. Like moth flowers, bat-pollinated flowers open and release their scents at night. Bats shove their whole heads into the flowers in order to reach the nectar with their tongues.

IN THIS CHAPTER

- Discovering the differences between plants and fungi
- Looking at the fungal lifestyle
- Exploring the world of fungi

Chapter 17

I'm Not a Plant, But I'm a . . . Fungi

Fungi are fascinating and mysterious organisms. They look a little bit like plants, but they have a completely different lifestyle. They can be a very nutritious addition to your diet, but they can also be deadly poison. In this chapter, we look at the importance of fungi to people and take a close look at how they live their lives.

Meet the Neighbors

Many people think fungi are closely related to plants. Some of them look rather plantlike, and they're often found growing among plants or even *on* plants. But if you look closely, the first thing you might notice is that they aren't green. And when you look really closely, like with a microscope, you'll find out that the parts of the fungi that you can actually see are only a tiny fraction of the entire organism. Taking a peek into the lives of fungi reveals many secrets about how they live and how they can help and hurt humans.

What is a fungus, anyway?

WARNING

Fungi aren't plants. They don't have chloroplasts and they don't photosynthesize.

Like plants, fungi have eukaryotic cells that are surrounded by a cell wall. However, the cell wall of fungi is mostly made from chitin, rather than cellulose. (*Chitin* is a nitrogen-containing polysaccharide that is also found in the exoskeletons of arthropods like crabs and insects.) These cells grow into long filamentous chains of cells called *hyphae* (pronounced *hy-phee*). Fungi are also known for things they don't have: They don't have chloroplasts, and they never produce cells that have flagella (most plants, on the other hand, produce sperm that swim by flagella).

REMEMBER

Fungal hyphae spread through the environment, weaving together to form networks called *mycelia* (pronounced *my-see-lee-a*) like those shown in Figure 17-1. During sexual reproduction, the mycelia in some fungi form complex three dimensional forms we recognize as mushrooms, shelf fungi, puffballs, and stinkhorns.

Like plants, fungi have fairly complicated life cycles. They reproduce by *spores*, which are single cells that can produce a new individual. Fungi have the ability to make spores by either sexual or asexual reproduction (for a review on these types of reproduction, head back to Chapter 9).

Fungi are *heterotrophs*, which means they eat others, and *decomposers*, which means they eat the dead (head to Chapter 20 for more about the role of decomposers in ecosystems). Their hyphae penetrate into materials and release digestive enzymes. These enzymes break down the large food molecules (like proteins, carbohydrates, and fats) in the environment, allowing the fungi to absorb their smaller components (like amino acids, simple sugars, and fatty acids) into their cells. Because fungi digest food outside of their bodies and absorb the small components, they're sometimes called *absorptive heterotrophs.*

In addition to their role as decomposers, fungi form important symbioses with plants and algae (for more on symbiosis, flip to Chapter 20).

REMEMBER

Mycorrhizal fungi in the soil form long-term partnerships (symbioses) with plants. These fungi attach to the roots, either as a covering on the surface (ectomycorrhizae) or by actually penetrating into and growing within root cells (endomycorrhizae). (Mycorrhizae are illustrated in Figure 17-1.)

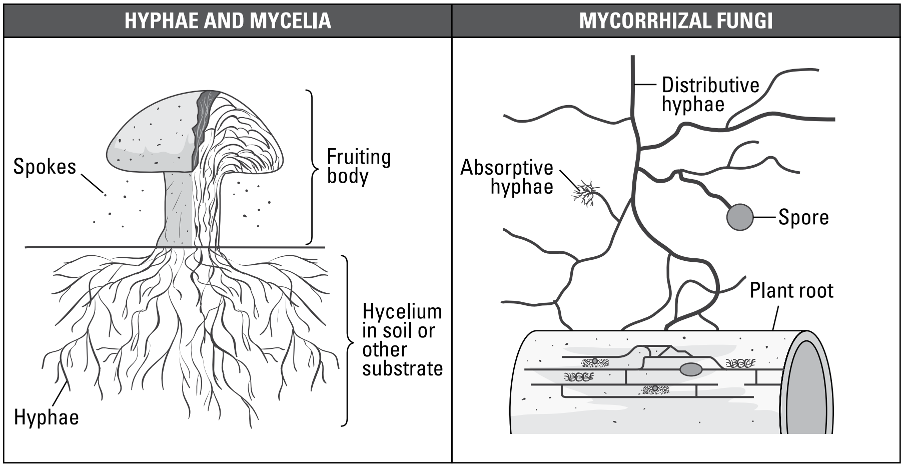


FIGURE 17-1: How fungi grow.

Mycorrhizae extend through the soil away from the plant roots, absorbing water and minerals and passing them back to the plant. This greatly increases the area available to the plant to obtain what it needs to grow and increases its resilience in times of stress. In exchange, the plant provides the fungus with sugars made through photosynthesis.

A similar partnership exists between fungi and algae to form the *lichens* you've probably seen growing on rocks and trees. In this partnership, the fungal mycelium essentially builds a drought-resistant house for the algae to live in, whereas the algae perform photosynthesis and feed the fungus. Most of the fungi that form lichens belong to the sac fungi, whereas most of the algae are either green algae or cyanobacteria (both discussed in Chapter 13).

REMEMBER

Lichens can be flat and scaly (*crustose*), leafy-looking (*foliose*) or have three-dimensional structures that almost make them look like mosses (*fruticose*). Mosses, however, are true plants (discussed in Chapter 14), whereas lichens are a partnership between a fungus and an alga.

There's a fungus among us

Fungi have definitely made their mark on human history. A mold growing on some plates in Dr. Alexander Fleming's lab led him to discover the first antibiotic, penicillin (from the mold *Penicillium*). Ergot (*Claviceps purpurea*) is a fungus that infects cereal crops like rye. It produces powerful psychoactive chemicals, including LSD. People who eat food contaminated with fungus may experience violent spasms, hallucinations, and blackening of their fingers and toes due to gangrene. People used to call these symptoms "St. Anthony's Fire" or the "Devil's Curse" and thought they were of divine or demonic origin, leading to some sufferers being burned at the stake as witches. Some historians think ergot poisoning led to the infamous witch trials in Salem, Massachusetts. Both *Penicillium* and *Claviceps* are members of the sac fungi shown in Figure 17-2.

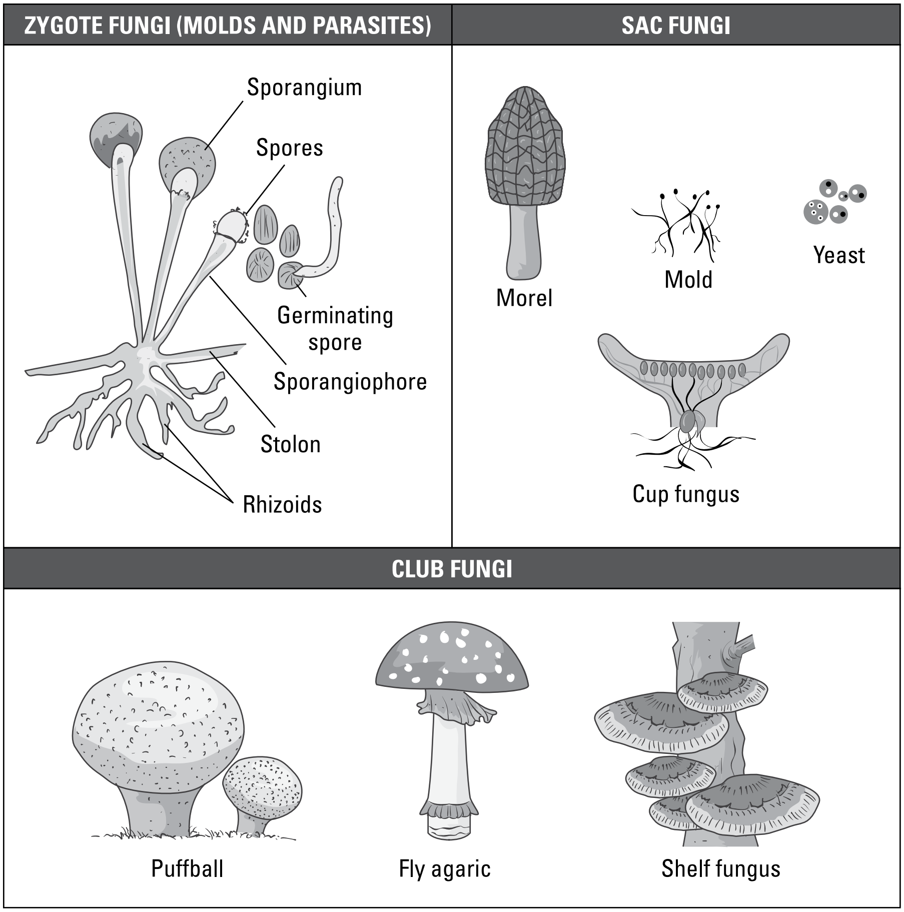

ZYGOTE FUNGI (MOLDS AND PARASITES)
Sporangium
Spores
Germinating spore
Sporangiophore
Stolon
Rhizoids
SAC FUNGI
Morel
Mold
Yeast
Cup fungus
CLUB FUNGI
Puffball
Fly agaric
Shelf fungus

FIGURE 17-2: Major groups of fungi.

REMEMBER

Many fungi produce powerful chemical compounds that can cause hallucinations or even death.

The mysterious way that some fungi grow have also led people to connect them with fairies. Sometimes, people will come upon a group of mushrooms growing in a near perfect circle. This arrangement seemed too magical to have happened by chance, leading people to name them "fairy rings." People thought they were places where fairies came to play and that they might be dangerous, especially if you entered one at night.

I can't say for sure whether fairies like to play in these mushroom circles, but I can tell you why some mushrooms grow like this. If a fungus starts growing from a single spot, it will send its hyphae out from that point in all directions, forming an invisible circular mycelium that's spreading through the ground. As the hyphae travel outward, they digest all the food along the way, so they just keep spreading out further and further. If the fungus receives the right signals, it will enter sexual reproduction, and the hyphae will switch into forming the *fruiting body* (reproductive structure), which, in the case of fungi that form fairy rings, is a mushroom in the club fungi group shown in Figure 17-2. These mushrooms form at the tips of all the hyphae simultaneously (remember this is one organism), so what you get is a near-perfect circle that marks the edge of the fungus's domain.

A different kind of magic can be found in "magic mushrooms," which are mushrooms in the genus *Psilocybe* that produce the psychoactive compound psilocybin. Psilocybin alters a person's state of consciousness and can change your perception of what you see and hear. People may feel very strong emotions and physical symptoms such as nausea and elevated heart rate. *Psilocybe* mushrooms play an important role in some religious ceremonies in Mesoamerica. Some people around the world use them recreationally and scientists are currently testing psilocybin as a potential treatment for some mental health conditions.

Fungal feasts: fabulous or foul?

Fungi are clearly skilled chemists, with the power to alter our brain chemistry and even kill us. So, you might wonder, why do we eat them? Well, my first answer, which you may not agree with, is that they are delicious! If you are vegetarian or vegan, mushrooms can be a great way to provide umami flavor to your foods. Humans have foraged for fungi probably as long as there have been humans, and even figured out that they could use pigs to sniff some of them out. At least since the Renaissance, people in Europe used truffle hogs to sniff out truffles, which are members of the sac fungi in the genus *Tuber*. Pigs have great noses and can smell a chemical in the fungus even if they are three feet underground! Nowadays, people have switched to using trained dogs to locate truffles because the pigs did a little too much damage to the mycelia during the hunt.

Another excellent reason for eating fungi is that they are great for your health. Fungi contain a high percentage of diverse complex carbohydrates (also called dietary fiber). As your gut microbes digest the fungi, they produce short chain fatty acids that have many beneficial health benefits, like regulating your blood lipids, preventing cancer, and even boosting your mood.

REMEMBER

Fungi are highly nutritious prebiotics. A *prebiotic* is something you eat because it will encourage the growth of the microbes in your gut. (A *probiotic* is something you eat that actually contains live microbes thought to benefit your health).

This introduction to the fungi wouldn't be complete without mentioning yeast because they've have been partners in human food production for thousands of years. Cultures all around the world use them to make beer, bread, and wine. Yeast grow differently than other fungi: instead of growing as hyphal threads, they grow as single, oval cells (check them out in the sac fungi in Figure 17-2). When they reproduce asexually by mitosis, the cells divide unevenly so that one cell looks like a baby cell growing off the larger cell. (For a refresher on asexual reproduction and mitosis, head back to Chapter 9). This unique-looking cell division makes yeast fairly easy to recognize when you look at them through a microscope.

REMEMBER

Yeasts reproduce asexually by a process called *budding*, in which the cytoplasm is initially divided unequally between the two cells that result from mitosis.

In the sections below, I take a closer look at how each of the major groups of fungi grow and reproduce.

You've Seen Us in Your Kitchen

If you've ever seen mold with fuzzy black spots growing on your bread, you've seen an example of a *zygote fungus* like the ones shown in Figure 17-2. These fungi get their name from the *zygospore* they make during sexual reproduction (see Figure 17-3). Another characteristic these fungi have in common is that they're *coenocytic*, meaning they don't build cross-walls between the cells in their hyphae. (Imagine a drinking straw filled with cytoplasm and organelles and you get the idea.)

Scientists used to classify all of the fungi with these characteristics into one phylum, the Zygomycota, but based on recent DNA analysis, they've split them into two phyla: the Mucoromycota (mostly parasites of small animals) and Zoopagomycota (which includes bread and fruit molds, some mycorrhizal fungi, and a couple of human pathogens). Most people refer to zygote fungi by common names such as mold, bread mold, sugar mold, and pin mold.

For a zygote fungus, life begins when a spore begins to grow (*germinates*) into a hyphal thread. The spores and growing hyphae of zygote fungi are haploid, meaning that each nucleus only contains one set of chromosomes (for a review on haploid and diploid, flip back to Chapter 9). The hyphae grow by mitosis into mycelia.

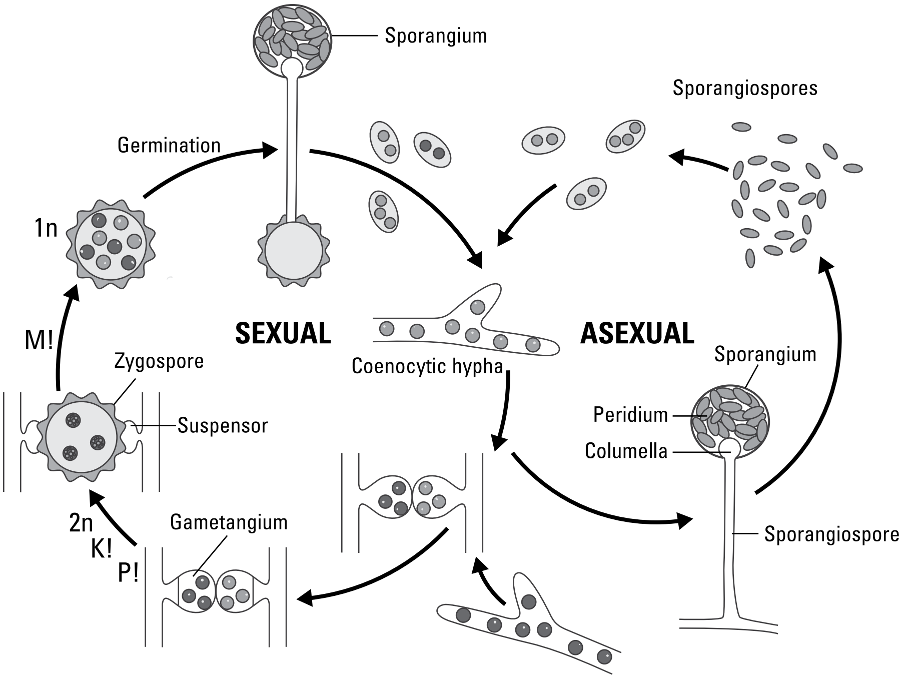

Sporangium
Sporangiospores
Germination
1n
SEXUAL
ASEXUAL
M!
Zygospore
Coenocytic hypha
Sporangium
Suspensor
Peridium
Columella
2n
K!
P!
Gametangium
Sporangiospore

FIGURE 17-3: Life cycle of a zygote fungus (*Mucor* sp.).

Zygote fungi can reproduce both asexually and sexually, although asexual reproduction is more common:

- During asexual reproduction, shown on the right side of Figure 17-3, some hyphae produce a structure called a *sporangium*. Inside the sporangium, mitosis produces single-celled *spores* that can disperse and grow into new hyphae. (When you see black or green dots on the mold growing on your food, you're probably seeing these sporangia.)
- Sexual reproduction, shown on the left side of Figure 17-3, only occurs if two fungi of *opposite mating types* grow near each other. Each fungus produces certain chemical hormones that have the ability to affect other individuals. Scientists call these fungi (+) or (–) strains depending on which hormone they produce.
  - When (+) and (–) strains grow near each other, their hormones cause their hyphae to form swellings called *gametangia*. Each gametangium contains several haploid nuclei.
  - The gametangia of the (+) and (–) strains fuse together, mingling their nuclei in one space. The nuclei fuse together, creating diploid nuclei that contain the genetic information from each fungus.
  - Scientists call the structure formed by the fusion of two gametangia a *zygosporangium*. A thick tough wall forms around the zygosporangium, which can remain dormant for long periods of time.

  - When environmental conditions signal the zygosporangium that conditions are favorable for growth, the zygosporangium germinates to produce a new sporangium. At the same time, meiosis occurs in the diploid nuclei, producing new haploid spores.
  - The sporangium releases the haploid spores and they can grow into new hyphae.

REMEMBER

During asexual reproduction of zygote fungi, haploid cells in the sporangium divide by mitosis to produce haploid spores that have the same genetic material as the parent fungus. During sexual reproduction, nuclei from two different fungi fuse together, then undergo meiosis to produce haploid spores that contain genetic material that came from two different parents.

Morels, Yeast, and Zombie Fungi

Sac fungi, or members of phylum Ascomycota, include many fungi you may be familiar with, such as yeast, delicious truffles and morels, and even the infamous *Cordyceps* fungi that can alter the behavior of insects like ants, creating "zombies" that still move but engage in behaviors that benefit the fungi, not the ants. The ascomycetes also include economically important species like the *Aspergillus* that help ferment rice wine to make sake, species of *Penicillium* that turn milk solids into cheese like camembert, and several plant pathogens that affect crop plants.

The hyphae and mycelia of ascomycetes contain haploid nuclei. These fungi can reproduce both asexually and sexually:

- During asexual reproduction in most ascomycetes, shown in the lower right of Figure 17-4, some hyphae produce a structure called a *conidium*. Cells from the conidia divide by mitosis to produce haploid *conidiospores.* These spores can germinate into new hyphae that are genetically identical to the original fungus. In many species of ascomycetes, the conidium is swollen like the palm of a hand, and chains of conidiospores extend outward from the conidium, looking like little fingers extending from the palm. Another way people describe these structures is that they look like little witches' brooms.
- During sexual reproduction, shown in Figure 17-4, two hyphae fuse together, combining their nuclei in a structure called an *ascogenous hypha*.
  - In some species, two hyphae from genetically identical clones can fuse together, while in other species the two hyphae must be from genetically different clones. One of the two hypha is called an *ascogonium*, whereas the other is called an *antheridium*.

- The ascogenous hypha that contains nuclei from both parents begins to grow and form a reproductive structure. Depending on the species, this might appear to your eye as a cup fungus, a shelf fungus, or even the mushroom-like morel. Within the reproductive structure, pairs of nuclei get walled off in special cells.
- The pairs of nuclei from the two parents fuse together, creating a single-celled diploid zygote. This cell elongates into a sac-like structure called the *ascus*, which is unique to this group of fungi (and is why they're called *ascomycetes*).
- Meiosis occurs, producing haploid *ascospores* that are genetically unique from the original parents. If you were to use a microscope to look at the reproductive structure of an ascomycete, you would see that it is lined with rows of the elongated asci, each one filled with ascospores. The asci release the ascospores, and they can grow into new individuals.

REMEMBER

During asexual reproduction of sac fungi, haploid cells form a sporangium called a *conidium*, which produces haploid *conidiospores* by mitosis. During sexual reproduction, haploid nuclei fuse, creating a zygote that grows into an elongated cell called an *ascus*. Meiosis occurs to produce haploid ascospores that are genetically different from the original parents.

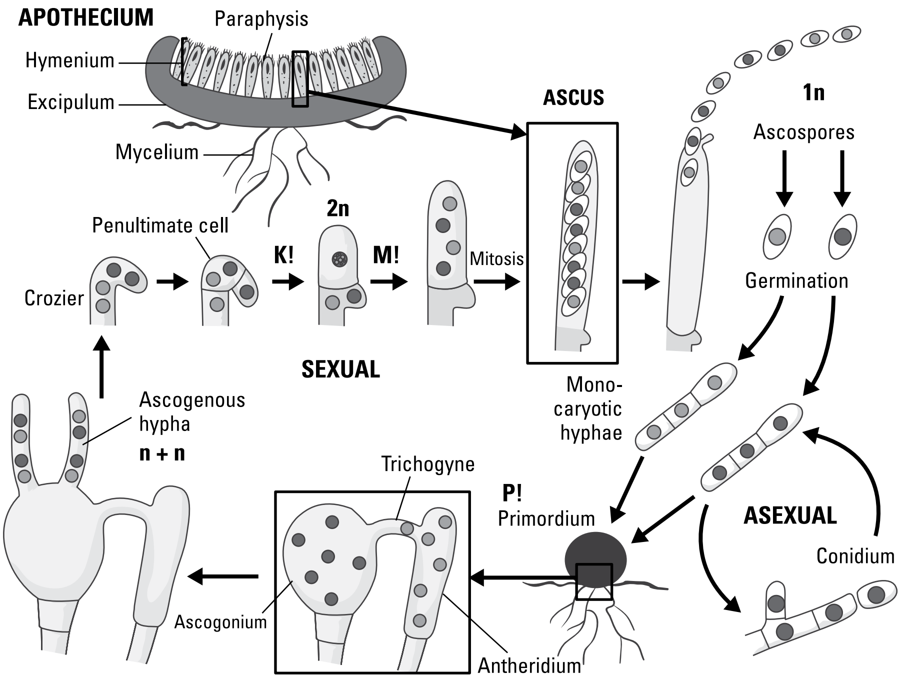

APOTHECIUM
Paraphysis
Hymenium
Excipulum
Mycelium
ASCUS
1n
Ascospores
2n
Penultimate cell
K!
M!
Mitosis
Crozier
Germination
SEXUAL
Mono-
caryotic
hyphae
Ascogenous
hypha
n + n
Trichogyne
P!
Primordium
ASEXUAL
Conidium
Ascogonium
Antheridium

FIGURE 17-4: Life cycle of sac fungi (*Pezizales* sp.).

Puffballs, Stinkhorns, and Mushrooms

Club fungi, or members of the Basidiomycota, include most of the things you would call mushrooms — oyster mushrooms, chantarelles, portabellas, and shiitakes, to name just a few. In this group you also find some shelf fungi, puffballs, and stinkhorns, as well as the plant pathogens commonly referred to as rusts and smuts.

Life begins for a basidiomycete when a haploid spore germinates and grows into a hypha that contains haploid nuclei of just one type. When this hypha encounters another hypha of opposite mating type, they fuse together, combining their two different types of nuclei into one mycelium. Because this mycelium contains two different kinds of nuclei, scientists refer to it as *dikaryon*, as shown in Figure 17-5. This dikaryotic mycelium is the dominant phase of basidiomycetes, meaning they spend most of their life cycle in this phase and may continue to grow this way for many years.

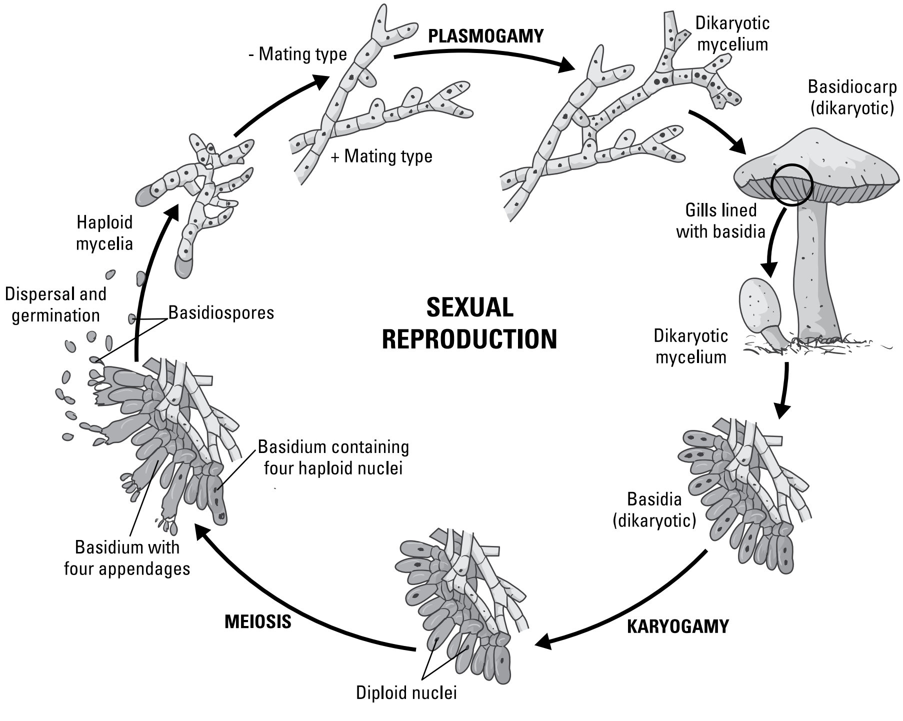

- Mating type
PLASMOGAMY
Dikaryotic mycelium
+ Mating type
Basidiocarp (dikaryotic)
Gills lined with basidia
Haploid mycelia
Dispersal and germination
Basidiospores
SEXUAL REPRODUCTION
Dikaryotic mycelium
Basidium containing four haploid nuclei
Basidia (dikaryotic)
Basidium with four appendages
MEIOSIS
KARYOGAMY
Diploid nuclei

FIGURE 17-5: Life cycle of club fungi.

Most basidiomycetes reproduce sexually:

- In response to environmental signals, the dikaryotic mycelium begins to grow into a fruiting body, such as a mushroom.
- Within cells of the fruiting body, pairs of nuclei in the hyphae that came from both parental strains fuse together forming a diploid zygote.
- The cell that contains the zygote grows into a club-shaped structure called a *basidium*.
- Meiosis occurs within the basidium, producing haploid nuclei that migrate to the surface of the basidium and form *basidiospores*.
- The fungus releases the basidiospores and they germinate into new haploid hyphae that contain one type of nucleus.

REMEMBER

Basidiomycetes spend most of their life cycle as dikaryotic mycelia. Within the fruiting body, the nuclei fuse, then undergo meiosis within the basidium to produce haploid basidiospores. The basidia form along the edges of the fruiting body, for example, along the gills on the underside of a mushroom.

5

Embracing the Synergy of Plants and People

IN THIS PART . . .

Reflect on all the ways plants are essential to people's lives

Explore the history of how humans have shaped the plants we use as foods

Discover the importance of plants in our ecosystems

Find out how plants are connected to the carbon cycle and global warming

IN THIS CHAPTER

- Connecting with plants
- Making useful products from plants
- Healing with plants

Chapter 18

Exploring the Relationship Between People and Plants

Plants are intimately entwined in people's lives. They provide us with many essentials, from the more well-known things like oxygen and food to more subtle services like helping keep our water clean and providing food and shelter for animals. We use plants to make homes, clothing, and useful household items. Plants can heal us too, by providing powerful chemicals that we take as medicine or by helping people connect with nature to calm their minds. In this chapter, I explore the many ways plants support and enrich our lives beyond providing us with food. (I tackle that subject in Chapter 19.)

Finding Our Favorites

What is your favorite plant? Do you have a favorite fruit or flower? Maybe you remember a stunning tree you saw while hiking, or someone you love grew something special in their garden? If you close your eyes and think for a moment, you can likely think of a plant or two that has a special meaning in your life. (My special plant is parsley because it reminds me of my grandparents' garden.)

People connect with plants for many different reasons, but there is one reason that unites most people in the world in their love of at least one of three particular plants — the sources of coffee, tea, and chocolate. The not-so-secret reason that people love these plants is because we find them so stimulating: these plants all contain the chemical caffeine, which acts as a stimulant to our nervous systems. In fact, people like caffeine so much that ancient groups of people all around the world discovered and remembered whatever plants in their region contained this chemical! (Besides the three plants discussed in this chapter, caffeine is also found in yerba mate, a South American beverage made from the leaves of *Ilex paraguariensis*, guarana, an Amazonian plant called *Paullinia cupana* that is added to many of today's energy drinks, and the nuts from West African *kola* trees, which were originally used as flavoring in cola drinks.)

REMEMBER

Caffeine is an alkaloid that stimulates the central nervous system. It can improve learning and performance on tasks that require short-term memory. At low doses it can even help relieve anxiety. The USFDA says that doses of up to 400mg per day are generally safe. At high doses (1200 mg), however, *caffeine toxicity* can occur, leading to increased anxiety, agitation, heart palpitations, and even seizures. Overconsumption of caffeine pills or powders can lead to a lethal dose.

Coffee

The coffee plant, *Coffea arabica*, is an evergreen shrub that's native to the highlands of modern-day Ethiopia. It produces small white flowers that develop bright red fruits that people call coffee berries or coffee cherries. The hard seeds within the coffee berries are the coffee "beans" that people eat or roast and grind to make liquid coffee.

REMEMBER

Coffee berries are technically *drupes*, because they are fleshy fruits that have a hard inner layer (endocarp) that surrounds the seed and because they don't split open when ripe. Most drupes, like peaches, plums, and cherries, have a single seed inside the "pit," but coffee berries typically have two seeds, which people call coffee beans.

According to legend, coffee was discovered when a young goat herder noticed that his goats were leaping about so much they seemed to be dancing. When he went to see why they had so much energy, he found that they'd been snacking on the red berries from an evergreen shrub. The goat herder tried the berries himself and got a similar boost in alertness. He shared his discovery with local monks, and coffee began to move along human trade and travel routes, until today it is consumed all around the world in different forms. In many cultures, drinking coffee with other people is an important social ritual.

Coffee beverages can be prepared in different ways, but there are a few steps that are common to most preparation:

1. **Separate the coffee beans (seeds) from the fleshy part of the fruit.** The traditional way to do this is to allow the coffee berries to dry in the sun. The natural yeast on the berries will ferment the sugars, giving unique flavors to the drying beans. Once the fruit is dried, the beans are separated from the dried skins. A newer approach is to remove the beans from the berries immediately, then place the beans in a vat of water. The yeast will begin fermentation, removing the remaining soft parts of the fruit that is stuck to the beans.
2. **Dry the beans.** If using the wet method of separation, the beans need to be spread out and dried after they've fermented in the vat.
3. **Roast the beans.** Different combinations of temperature and time lead to different roasts on the beans, typically ranging from light to dark roasts. The lighter the roast, the greater the amount of caffeine that remains in the beans. The darker the roast, the less caffeine and the more the oils from the beans will rise to the surface, which contributes to the flavor of the coffee.
4. **Grind and brew the beans.** The grinding and brewing of coffee varies quite a bit, depending upon whether you're making a concentrated shot of espresso or Turkish coffee or brewing an American-style cup of joe.

REMEMBER

The process of *fermentation* is an important step in the production of coffee beans for beverages. During fermentation, yeast (and bacteria) break down the sugars in food for energy, producing acids and ethanol as waste products. This process doesn't require oxygen.

As coffee spread around the world, people from many tropical areas successfully grew it in their own lands. Coffee is still grown in Ethiopia and other parts of Africa, but Brazil, Vietnam, and Colombia are the world's largest coffee producers. In addition to *Coffea arabica*, many coffee farms grow another species, *Coffea canephora* (aka "robusta"), which contains more caffeine and has a stronger flavor.

REMEMBER

In addition to the alkaloids caffeine and theobromine (discussed in the section on chocolate below), coffee also contains other types of plant secondary chemicals, like phenolics, flavonoids, and terpenoids. These molecules contribute to the flavor of coffee and can also affect the human body. For example, many flavonoids have antioxidant activity and the chemicals in coffee have been shown to reduce blood lipids, blood sugars, and may even help prevent some neurodegenerative diseases.

Tea

Real tea comes from the leaves of the tea plant, *Camellia sinensis*. The tea plant is native to the area around southwestern China and has been cultivated in that country for 2000 years. Today, the evergreen shrub grows in tropical and subtropical areas all around the world, with China and India producing the most. If you live in a place that's dominated by coffee culture, it might surprise you to learn that tea is the second most commonly consumed beverage in the world, with only water ranking higher.

WARNING

Many people drink beverages they call *herbal tea* that are made from various plants. To a tea purist, these aren't tea at all, but rather *tisanes*. To be properly called tea, the beverage must be made from dried leaves of the tea plant.

People typically harvest tea by pinching off the tips of branches, taking the buds and two or three young leaves. The harvesting process can be repeated every couple of weeks as the plants continue to grow. The harvested leaves are exposed to the air so that oxygen can react with the chemicals in the tea leaves. Longer exposure to air allows greater oxidation of the leaves, changing the chemistry of the leaves and creating different varieties of tea. In general, the greater the oxidation time, the darker the color of the tea leaves and the more caffeine in the final tea.

- **White tea** is made from the youngest leaves, which are picked early. They dry quickly so very little oxidation occurs, and the tea is low in caffeine.
- **Green tea** is made from larger leaves, which are heated after harvest to stop oxidation. Usually only a little oxidation occurs, so this tea is also low in caffeine.
- **Oolong** comes from tea leaves that oxidize for variable lengths of time, producing tea that is anywhere from 20-80 percent oxidized. This tea is darker in color and contains more caffeine than green or white tea.
- **Black tea** comes from tea leaves that fully oxidize. People chop or shred the leaves so there's more surface area for exposure to oxidation. This type of tea contains the most caffeine.

Oxidation is a chemical process through which molecules lose electrons. Oxygen has a strong pull for electrons, which is why exposure to our atmosphere leads to oxidation. For example, when metal containing iron is left outside, it will rust as the iron oxidizes. When people expose tea leaves to the atmosphere, the oxygen reacts with the secondary chemicals in the leaves, leading to changes that affect the flavor of the tea. Oxidation also helps break down the plant cells, which helps release more caffeine when the tea is brewed.

Two types of tea go through additional processing:

- **Pu'erh tea**, also known as fermented tea, undergoes fermentation after oxidation. After the leaves completely oxidize, people roll them into cakes, then place them in caves. The microbes from the caves fall onto the cakes and begin the fermentation process, giving the tea a very earthy flavor. This tea was highly prized in southern China and is now very popular in France. It's very low in caffeine and has been shown to decrease blood cholesterol.
- To make **matcha**, people cover the tea plants for 20 days before they harvest them so that the leaves don't get any light. The leaves are picked and steamed immediately to stop oxidation. People pull the vascular tissue out of the leaves, then grind them into a fine green powder. When you drink matcha, you aren't just drinking chemicals released from tea leaves into the water, you're consuming the actual plant material of the leaves.

REMEMBER

Oxidation is the loss of electrons, whereas fermentation is a complex, many step process by which cells break down sugars without the use of oxygen. Oxidation occurs during the fermentation process, but oxidation and fermentation aren't the same thing.

Two legends explain the discovery of tea. According to one legend, the Chinese emperor Shen Nung always wanted his water boiled before he drank it. One day, a leaf from a tea plant blew into the water as it was boiling. The emperor tasted the brew and enjoyed the delicate flavor. Another legend states that a Buddhist monk named Bodhi Dharma kept falling asleep while he was trying to meditate. He grew so frustrated that he ripped off both his eyelids and threw them on the ground. From where they landed, the first tea plants grew. Although the first legend seems a little more likely, the Buddhist monks played an important role in the movement of tea around the globe.

REMEMBER

In addition to the alkaloid caffeine, tea contains other types of plant secondary chemicals. The amino acid *theonine* works in conjunction with caffeine to improve alertness, cognition, and mood. Like coffee, tea contains a variety of phenolics and flavonoids that contribute to the flavor of tea and give it antioxidant properties. Scientific studies suggest that consumption of tea has health benefits, including the prevention of cancer and cardiovascular disease.

Chocolate

Chocolate comes from the tropical evergreen tree *Theobroma cacao*, whose name literally translates to "food of the gods." The tree produces large fruits called cocoa pods that can be up to a foot long and a pound in weight. Inside the fruit is a white pulp that surrounds many seeds, which are referred to as cocoa beans.

REMEMBER

Botanically speaking, a cocoa pod is a *berry*, because it is a simple fruit that has seeds and fleshy pulp and is produced from the ovary of a single flower. The things we call cocoa beans aren't actually beans, but rather the seeds from the berry.

A couple of things make *T. cacao* trees a little unusual. One is that they are *cauliflorous*, meaning they produce clusters of flowers directly along the trunk and older branches of the tree. (Cherry trees do this too — if you've ever seen flowers just sprouting off the trunk of a cherry tree, you've seen cauliflory in action.) The other thing that might seem a little weird is that the flowers are pollinated by small flies called midges. (Quite a few plants are pollinated by flies, actually, and if you think about what flies are attracted to, you might understand when I advise you not to take too deep a sniff from fly-pollinated plants — or just check out the discussion of the corpse flower in Chapter 21.)

T. cacao is native to Central and South America and was originally cultivated by the Olmec people in Central America. The Olmec made a beverage from the seeds of the tree as early as 1750 BC by crushing them and combining them with water, chilis, and other spices. Later, the Mayans and the Aztecs grew cacao trees and made similar beverages, which the Mayans called "chocolhaa" and the Aztecs called "Xocolatl." Our modern word *chocolate* probably came from a combination of these names. These drinks were probably bitter and spicy because they didn't contain any milk or sugar. Chocolate drinks were consumed during ceremonies and for medicinal purposes.

The initial steps to prepare chocolate from the fruit of the cacao tree are the same today as they were thousands of years ago:

1. **Scoop the seeds and pulp out of the fruit.**
2. **Leave the seeds mixed in the pulp for several days. Microorganisms will ferment the sugars in the pulp, releasing acids that will react with the seeds and help them develop their chocolate flavor. The seeds turn from a grayish color to a deep brown during this process.**
3. **Dry the seeds.**
4. **Roast the seeds.**
5. **Crush the seeds to create an oily paste called *chocolate liquor*.**

Chocolate liquor is the basis for all things chocolate. It's what the Olmecs, Mayans, and Aztecs used to make their drinks. In the United States, chocolate liquor is also called baking chocolate. You can remove the cocoa butter (fat) from chocolate liquor to create unsweetened cocoa powder. If you've ever tasted baking chocolate or unsweetened cocoa powder, you've experienced the bitter taste of the original chocolate.

Many people like the taste of bitter foods, but even if that was part of the appeal of the original chocolate drinks, there's probably more to the story of why people though it was a food of the gods (both the Mayans and the Aztecs had legends about how actual gods gave cacao as a gift to the people). The love of chocolate that spread around the world is probably due, at least in part, to the secondary chemistry of the cacao plant.

REMEMBER

The secondary chemical for which chocolate is most famous is called *theobromine*. Theobromine is an alkaloid related in structure to caffeine, and like caffeine, it can help make you more alert and boost your memory. Chocolate also contains caffeine itself.

WARNING

Theobromine can become toxic at high levels. People break it down fast enough that it isn't a problem for us. But dogs and horses break it down much more slowly, which makes chocolate much more likely to be toxic for them so be sure to keep chocolate away from your animals. And remember, the darker the chocolate, the more theobromine!

So, chocolate may have become popular for the same reasons that coffee and tea did — it's a way to get a boost to get you through your day. Chocolate also contains an alkaloid called *phenylethylamine*, which is known to promote feelings of well-being and happiness. This sounds like a great explanation for why chocolate makes some of us feel better, but some scientists say that this chemical would get broken down during digestion before it had any chance to work its effect on our brains. Similarly, we know cocoa beans are full of antioxidants, but many of these are lost during the processing of the beans so it's not clear if enough remain to have a positive effect on our health. So, for right now, it looks like we don't have solid health reasons to justify our consumption of chocolate. Those of us who love chocolate will just have to keep eating it because we like it!

Speaking of liking chocolate, how did we get from bitter chocolate drinks to today's confections such as a cup of sweet hot cocoa or a delicious chocolate bar? You may have already guessed the answer — it was the Europeans who put sugar in the chocolate. After Hernando Cortez drank chocolate with the Aztec emperor Montezuma, he brought some back to the Spanish court in the year 1528. The Spanish tried the bitter beverage and decided it needed a little sugar. From Spain, the custom of drinking chocolate slowly spread across Europe as cocoa beans became more available. The Europeans experimented with the processing of chocolate and different ways of preparing it until eventually the first chocolate bar was made in 1847 by the British chocolatier J.S. Fry and Sons who molded it from a paste made of sugar, chocolate liquor and cocoa butter.

Making Use of Plant Materials

If you look around the space you're currently in, you can probably spot many items made from plants. Was wood used in the construction of the building and the furniture? Are you wearing clothing made from cotton, linen, or hemp? Do you have a wooden pencil? Some paper? Maybe a basket woven from plant materials is sitting nearby? Even in our modern world where we have man-made materials such as plastic, steel, and glass, we're still surrounded by things we constructed out of plant materials. And, if you can imagine yourself in the past, or maybe on one of those survivalist TV shows, where they drop you on an island, maybe you can imagine a time when people made almost everything out of plants. They knew which plants and which plant parts were best for each need: broad leaves for roofing material, fibrous plants for rope or clothing, gourds for bowls and cups, or plants that could be woven for baskets. As groups of humans traveled around the globe to different environments, they found what they needed among the local plants.

Building homes

Wood, from both gymnosperms and angiosperms, is the most widely used construction material in the world. The demand for timber for construction increases pressure on the world's forests. Resource-rich nations, such as those in North America and Europe, have developed sustainable practices to meet their demand for timber. (*Sustainable* practices are those that can be maintained over time with minimal long-term effects on the environment.)

REMEMBER

Wood is formed from a secondary growth of plants. It is strong because of the lignin and other chemicals that plants deposit in their cell walls during this type of growth. (Refer to Chapter 2 for more details.)

Thus, even though North American and European countries are among the global leaders in timber harvest, their remaining forests aren't being impacted as much as forests in other countries. Europe actually experienced gains in the overall size of their forests since 2000, but they've lost more of their mature forests. During this same period, forests in North America remained relatively stable. Both these regions compensate for timber harvest by replanting trees and contain large areas dedicated to forest plantations.

Unfortunately, other areas of the world are not currently harvesting their timber sustainably. In particular, South America and Africa are losing their forests at a staggering rate. They're cutting their trees as fast as European countries do, but they don't have as many forest plantations — the trees they cut are often from native forests, leading to a loss in biodiversity.

REMEMBER

The amount of wood being used for construction can be determined by looking at the amount of sawnwood being produced. *Sawnwood* is wood that's been split into pieces of at least 5 millimeters in thickness, usually by sawing. Examples of sawnwood include planks, beams, joists, boards, and rafters.

Globally, European countries produce the most sawnwood, with North America coming in second. Sawnwood production in Asia and South America are both on the rise, where it is partially based on plantation grown timber.

In addition to raising trees for timber on forest plantations, another way to increase sustainability is to use *recycled wood,* also called *reclaimed wood.* Up to 40 percent of the wood from demolished buildings can be reused in new construction.

REMEMBER

Green construction, also called *green building or sustainable building,* is construction that maximizes efficient water, energy, and resource use and reduces waste, pollution, and environmental degradation. Green construction uses materials that are harvested sustainably, such as trees from sustainable plantations or rapidly growing materials such as bamboo.

Everyday Items

In addition to homes, people need clothing, cooking utensils, furniture, and many other useful items. Around the world, people have turned to plants to provide what they need for their everyday life:

- **Clothing:** Many plants contain *fiber cells*, which are cells that have extra-thick layers of cellulose in their cell walls. Fiber cells make certain plant tissues strong and useful for products such as clothing and rope.
    - Cotton provides almost half of the fiber that's used to make clothing and other textiles. It's planted on about 2.4 percent of the world's cropland spread over 90 countries. Together, these countries produce about 20 million tons of cotton per year. Unfortunately, cotton requires large amounts of water and pesticides in order to be a productive crop, which leads to negative impacts on surrounding ecosystems and the people who live there.
    - Hemp is a variety of *Cannabis sativa* that has very low levels of THC (tetrahydrocannabinol), the chemical that creates a pleasurable feeling. Hemp is grown for its fibers, which can be used to make rope, clothing, and paper. Hemp requires significantly less water than cotton and produces almost twice as much plant material per acre of land.

- **Household items:** Fiber cells and secondary cell walls make some plant tissues strong. People have learned how to access these tissues in many different plants and come up with various ways to shape plant materials into useful items.
  - Fruits such as gourds and pepos have hard outer rinds that remain after the fruit has dried, making these items useful for many items such as bowls, water jugs, and even musical instruments.
  - People carve wood into decorations, bowls, and spoons, and use it to assemble furniture and make musical instruments.
  - Strong and flexible plant materials like grasses, cattails, and even cedar bark can be woven into baskets, clothing, sleeping mats, and even walls or roofing material.
- **Energy:** We know that plants contain stored energy; after all that's why we eat them! Given our ever-growing need for energy, people are also trying different ways of using stored plant energy to fuel our homes and cars. In fact, the fastest growing sector in agriculture is in plants that can be used to generate biofuels. As fossil fuels, such as coal, oil, and gas, become less available, people are searching for alternative sources of energy. One solution to the energy crisis is to use plant material from plants that are alive today to make fuels, such as ethanol or biodiesel.
  - The process of making ethanol from plant material is shown in Figure 18-1. First, plant material, such as corn, is harvested and ground or milled into small pieces, producing a corn mash. Next, enzymes are added to the corn mash to break the large carbohydrates, such as cellulose and starch into smaller sugars. Finally, yeast is added to the corn sugar. The yeast performs *fermentation,* breaking down the sugar, and producing ethanol and carbon dioxide.
  - *Biodiesel* is diesel fuel made from plant products. Biodiesel can be made from plant oils, including waste oils from cooking processes. The plant oils are converted to biodiesels using lye and an alcohol like methanol.

REMEMBER

Biofuels are fuels made from organic matter such as plants, animals, or their byproducts from industrial processes. *Fossil fuels* are energy-rich hydrocarbon deposits formed in the earth from plant remains during a previous geologic age.

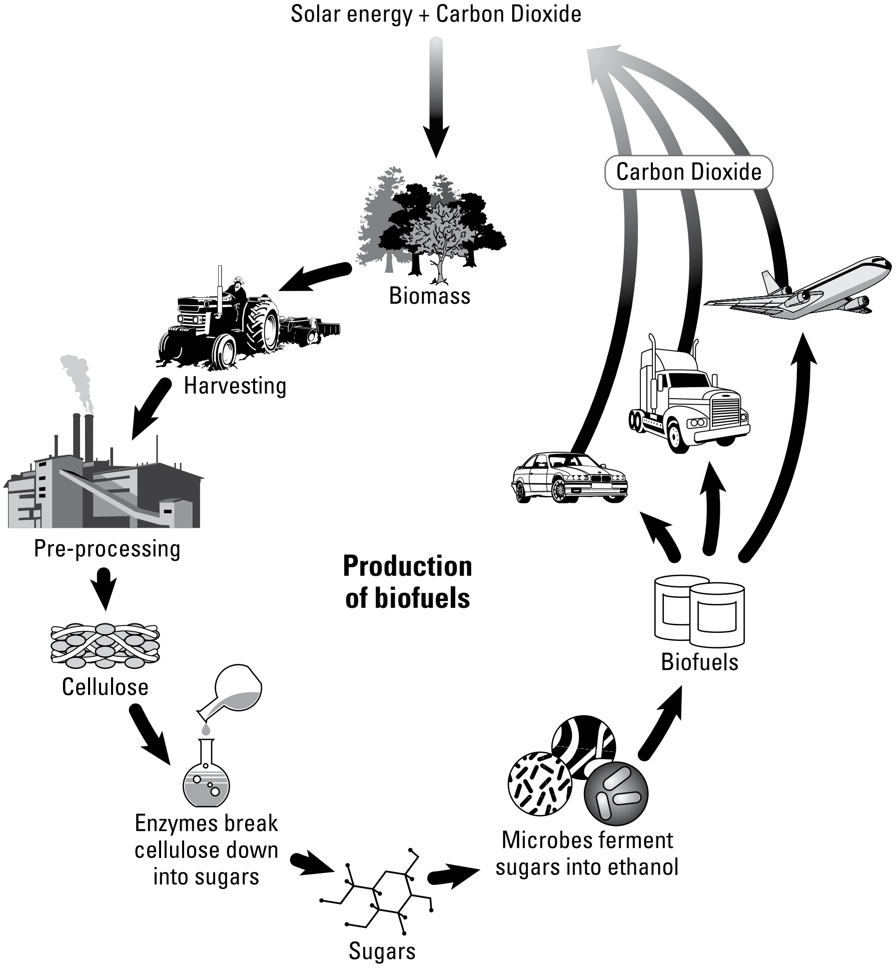

Solar energy + Carbon Dioxide
Carbon Dioxide
Biomass
Harvesting
Pre-processing
Production of biofuels
Cellulose
Biofuels
Enzymes break cellulose down into sugars
Microbes ferment sugars into ethanol
Sugars

FIGURE 18-1: Production of biofuels.

Making paper

About 42 percent of the world's commercial wood is used to produce the paper people use for writing, reading, wrapping, packaging, and wiping. Industrialized nations, which represent 20 percent of the world's population, use 87 percent of the world's printing and writing papers.

To make paper from wood, the cellulose fibers in the wood must be separated from the lignin that holds them together.

The paper-making process

Figure 18-2 shows the traditional process of making paper from trees:

1. **The wood is prepared for pulping by removing the bark and cutting the wood into smaller wood chips by using a machine called a *chipping machine*.**
2. **Wood is turned into pulp.**

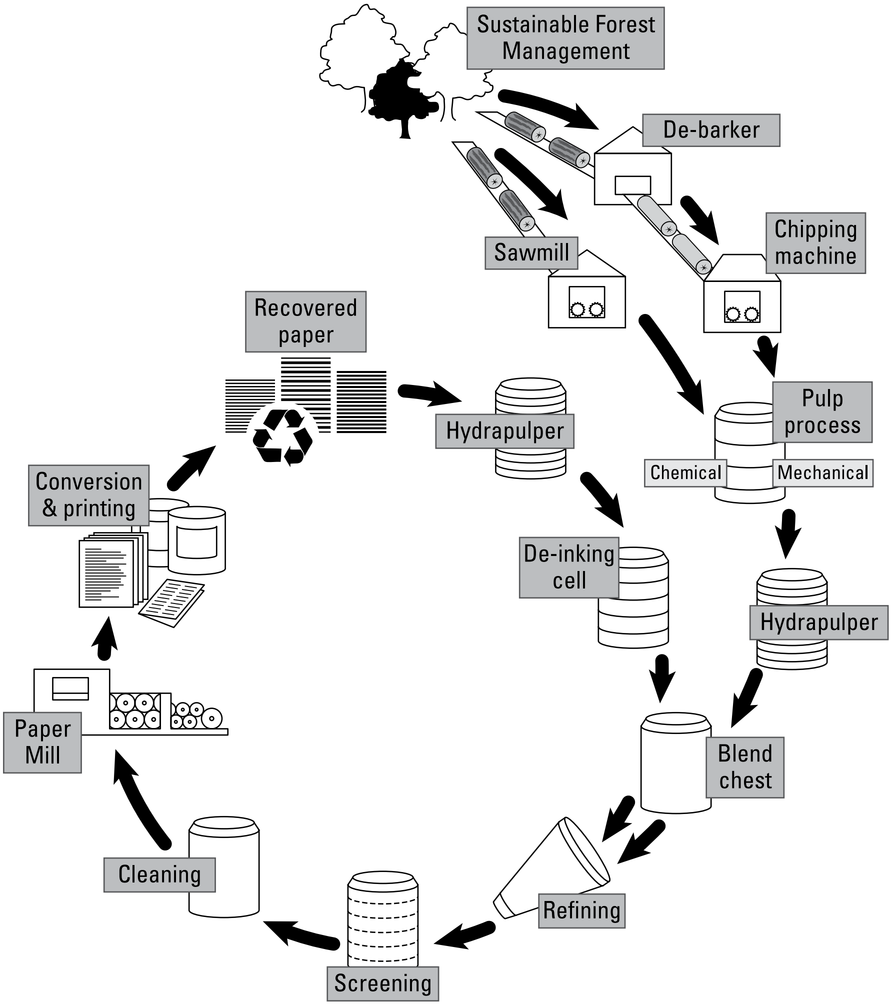

Sustainable Forest Management
De-barker
Sawmill
Chipping machine
Pulp process
Chemical
Mechanical
Recovered paper
Hydrapulper
De-inking cell
Hydrapulper
Blend chest
Refining
Screening
Cleaning
Paper Mill
Conversion & printing

FIGURE 18-2: Paper manufacturing.

3. **The wood pulp is combined with water in a hydrapulper, turning it into a thick pasty substance.**

   Recovered paper can also be used to make recycled paper. The paper is added to a hydrapulper and staples and other contaminants are removed by screening. The ink separates from the paper and is drained away in a process called *de-inking*.

4. **The paste from hydrapulpers passes into the blend chest, and chemicals and dyes are added to create the desired characteristics of the finished paper.**
5. **The paper paste from the hydrapulpers goes through refining as it is passed through a series of revolving metal disks to make it more flexible.**
6. **The paste is then passed through screens and spun rapidly in order to remove dirt and other undesirable materials during the process of screening and cleaning.**
7. **The paste is diluted with water as it enters the wet end of the papermaking machine, where it is rolled into sheets and then cut.**

Discovering the Power of Plant Chemicals

Plants produce an amazing array of powerful secondary chemicals. Many of these chemicals are part of the plant's defensive system, warding off potential predators by making the plant taste bad or even by outright poisoning them. Some plant chemicals have antimicrobial properties, while other molecules may act as signals. People have discovered these chemicals mostly by trial and error, finding the ones that act as medicines or poisons, those that we appreciate as spices in our food, and those that stimulate our central nervous system like caffeine. The knowledge about these useful plants was passed down from one generation to the next in cultures all around the world, and today, Western scientists are applying their methods to test the effects of some of these chemicals.

REMEMBER

Many of the world's most powerful medicines — and poisons — come from plants. In fact, sometimes the difference between a beneficial effect and a harmful one is just the amount of a particular chemical that a person is exposed to.

Finding a cure: Medicinal plants

People have used the bark and leaves of the willow tree to treat disease since ancient times. Chinese physicians used willow to relieve pain as early as 500 BC. Ancient Greeks, Egyptians, and Assyrians also used willow. For example, the Greek physician Hippocrates, who lived from 460 to 377 BC, suggested that women in labor should chew willow leaves for the relief of pain. People continued to use willow as a pain reliever and fever reducer throughout the world, and some people still use it today.

Although scientists and doctors discarded many ancient remedies as useless or even dangerous, the use of willow has stood the test of time. In fact, British chemists isolated the beneficial component of willow in 1828, a molecule called salicin. Scientists converted salicin to salicylic acid, and later to acetylsalicylic acid — in other words, aspirin!

REMEMBER

At least half of today's prescription medicines are derived from plant chemicals.

Figure 18-3 shows a few of the world's most beneficial plants:

- White willow, whose scientific name is *Salix alba*, contains salicin, which relieves pain, and reduces fever and inflammation. Today, aspirin is made from acetylsalicylic acid, which is synthesized in a lab.
- Foxglove, which botanists call *Digitalis purpurea*, produces digitalin, which is used to treat heart disease. Digitalin is used to make the medicines digitoxin or digoxin, which increase the force of heart contractions.
- Wormwood, or *Artemesia annua,* makes artemisinin, which has been used in Chinese medicine for many years under the name *qinghaosu*. It's become very valuable in recent years due to its antimalarial properties.
- Aloe is the transparent gel from inside the thick, succulent leaves of the *Aloe vera* plant. Aloe is used to treat wounds, burns, and other skin conditions.
- The happy tree, *Camptotheca acuminata*, is also called the tree of life and the cancer tree. This tree produces a compound called *camptothecin*, which has anticancer properties.
- Mormon tea, from the plant *Ephedra sinica*, has been used for many years in Chinese medicine under the name *ma huang*. The plant makes a chemical called ephedrine, which is a powerful stimulant and decongestant.
- The Pacific yew, *Taxus brevifolia,* makes the compound taxol in its bark. Taxol has anticancer properties and is particularly effective against breast and ovarian cancer.

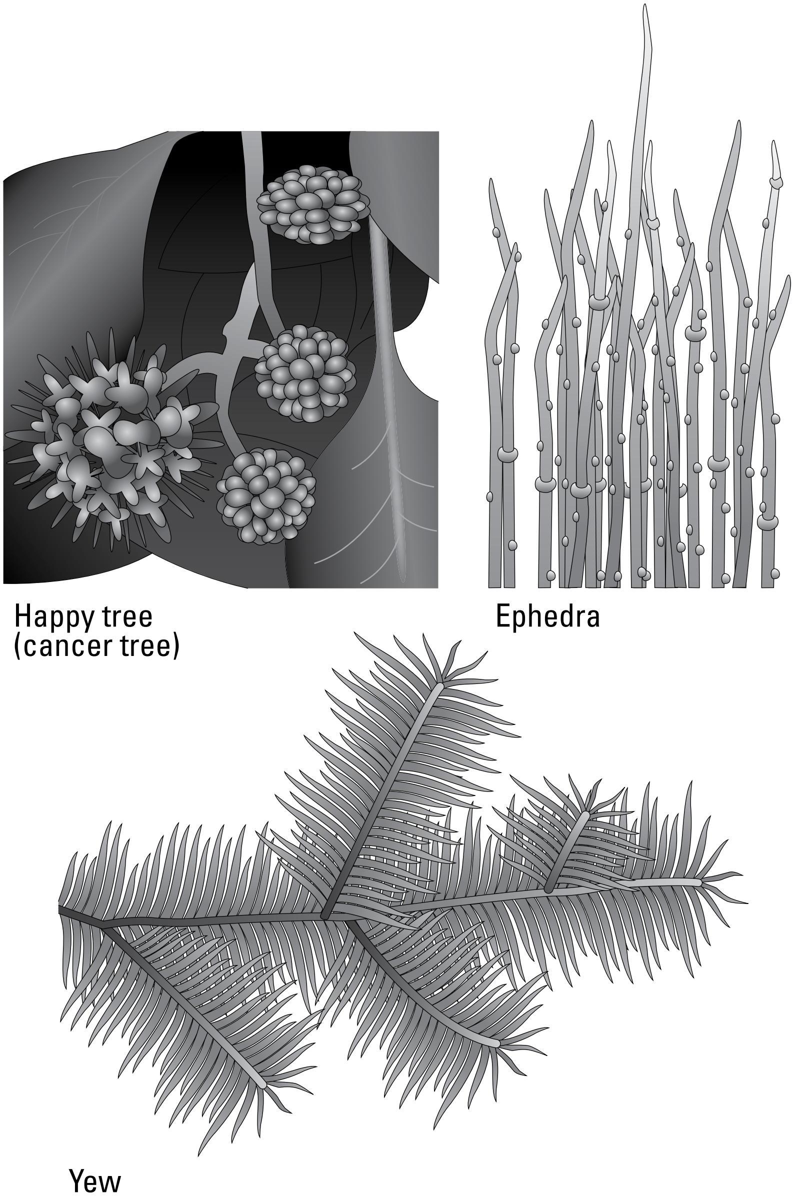


FIGURE 18-3: Medicinal plants.

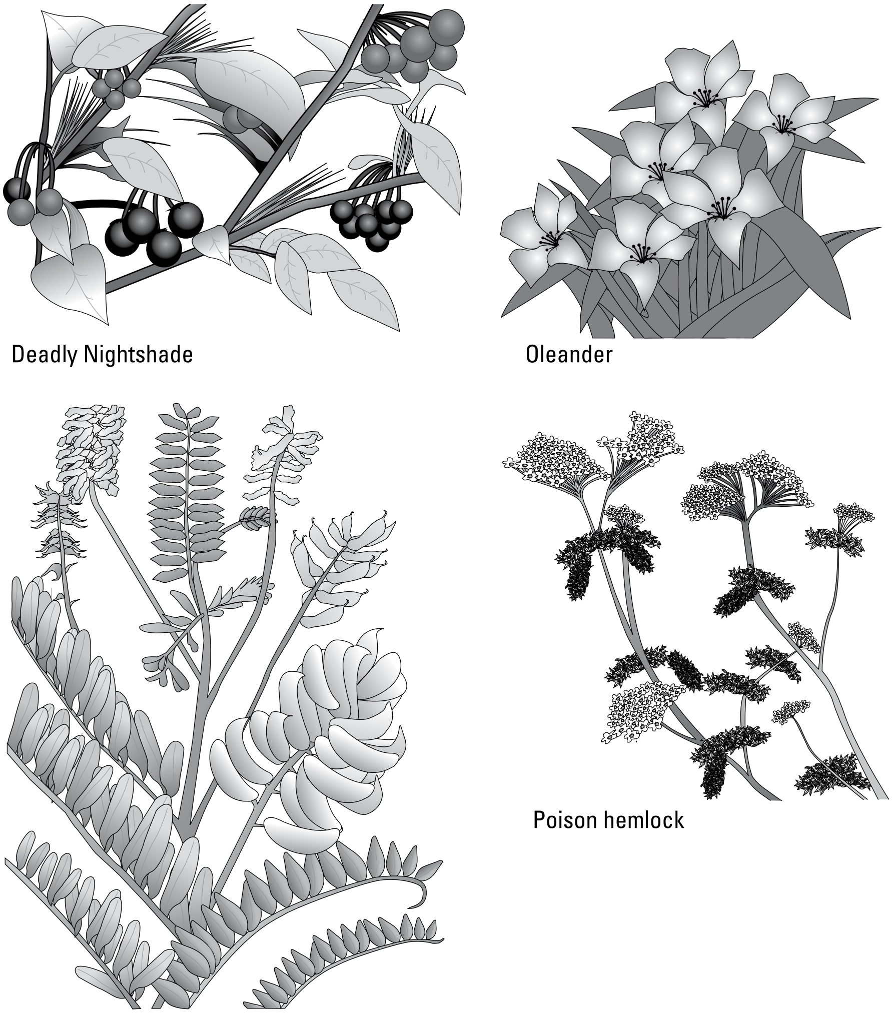
Dangerous weapons: Poisonous plants

The famous Greek philosopher, Socrates, was sentenced to death for his beliefs and ordered to drink a cup of poison made from hemlock. The poisoning of Socrates is one of the most dramatic examples of the power of poisonous plants, but many other more subtle examples surround us daily. Many common houseplants would be poisonous if you ate them, and animals, such as cows and sheep, can encounter poisonous plants while they graze.

Doctors have a saying, “The difference between medicine and a poison is the dose.” Plant chemicals are powerful, and many of them could be poisons if used incorrectly. For example, the digitalin from foxglove could stop your heart if you ate too much. Of course, some plants are more dangerous than others.

Figure 18-4 includes a few of the world’s most dangerous plants:

- Poison hemlock, or *Conium maculatum,* produces the poison coniine that is structurally similar to nicotine. Coniine affects the nervous system. In large doses, it leads to a slowed heart rate, paralysis, and coma. Death is usually from respiratory failure.
- Many people grow the oleander plant, *Nerium oleander,* as an ornamental plant in their yard. And yet, oleander is ranked at the top of many lists of most poisonous plants in the world. Oleander makes two powerful toxins, oleanderin and neriine, which are most concentrated in the leaves. In fact, occasional poisonings result from children chewing the leaves of this plant. The toxin is similar to the digitalin found in foxglove. If eaten by people or other animals, the toxin causes vomiting, diarrhea, and abdominal pain, as well as an irregular heart rhythm and eventual coma and death.
- Locoweed, which is the name for some plants in the genus *Astragalus,* gets its name from the effect it has on cattle that eat it — *loco* being the Spanish word for crazy. Cattle that ate locoweed must have appeared crazy as they became aggressive, walked with a stiff and clumsy gait, held their heads low, and went blind so that they staggered around crashing into things before they died. Different species of *Astragalus* produce different toxins, but the toxin swainsonine causes the crazy symptoms in cattle when it affects cells of the central nervous system. In lower doses, the toxin can also lead to birth defects. On a good note, some of the chemicals from species of *Astragalus* have anticancer activity.
- Deadly nightshade, or *Atropa belladonna,* produces shiny black berries that are sweet and juicy, occasionally tempting people to eat them. The berries and other parts of the plant contain two alkaloid toxins, atropine and scopolamine, which are deadly to humans and some animals. The poisons affect the nervous system, and if you eat enough of them, your involuntary muscles — including your heart — may become paralyzed. Before death arrives, your pupils dilate, and you experience sensitivity to light, blurred vision, headaches and confusion. When administered safely, however, the alkaloids from nightshade are beneficial — scopolamine is the main ingredient in a motion sickness patch, and atropine is used by opthalmologists to dilate their patients’ eyes.


Deadly Nightshade

Oleander

Poison hemlock

Locoweed

FIGURE 18-4: Poisonous plants.

- Death camas is a plant in the genus *Zigadenus.* They are delicate wildflowers that look like wild onions and often grow in areas where animals are grazing. Death camas produces alkaloid toxins that act on the central nervous system, leading to respiratory paralysis and death. Animals (especially sheep) that have eaten death camas are often found dead, lying near the plants they ate.
- Dumb cane, or *Dieffenbachia,* is considered one of the deadliest house plants and is also involved in livestock poisoning. The plants produce toxins called calcium oxalates in their sap. The toxin in the sap makes it very irritating to skin and mucus membranes. If the plant is eaten, the toxins cause burning and irritation of the mouth and tongue. The tongue may swell, leading to a

loss of speech in people. If the tongue swells too much, it can block air flow, leading to death by suffocation. South American Indians used the irritating power of dumb cane sap when making poisons for the tips of their arrows.

- Jimson weed, or *Datura stramonium,* grows as a weed in pasturelands and soybean fields. All parts of the plant are poisonous, but the most common cause of jimson weed poisoning is when grazing animals eat the leaves. The plant produces powerful toxins, including the chemical atropine, which is the same toxin produced by deadly nightshade. In small doses, atropine slows down the heart and dilates the pupils. In larger doses, atropine may induce hallucinations and lead to cardiac and respiratory arrest.
- Coffee (*Coffea arabica*), tea (*Camellia sinensis*), cocoa (*Theobroma cacao*), and kola nuts (*Cola* sp.) all produce caffeine. You might wonder what they're doing on this list — after all, people drink caffeine all the time, and they have been for a long time all over the world in all types of societies. In the doses that people usually consume caffeine (say 400 milligrams of caffeine, or the equivalent of two to four cups of coffee), caffeine isn't toxic. But in high doses, caffeine can cause restlessness, insomnia, and tremors and can even lead to seizures and heart problems. Some types of energy drinks have greater amounts of caffeine than coffee or tea, so it's a good idea to check your labels and watch your intake.

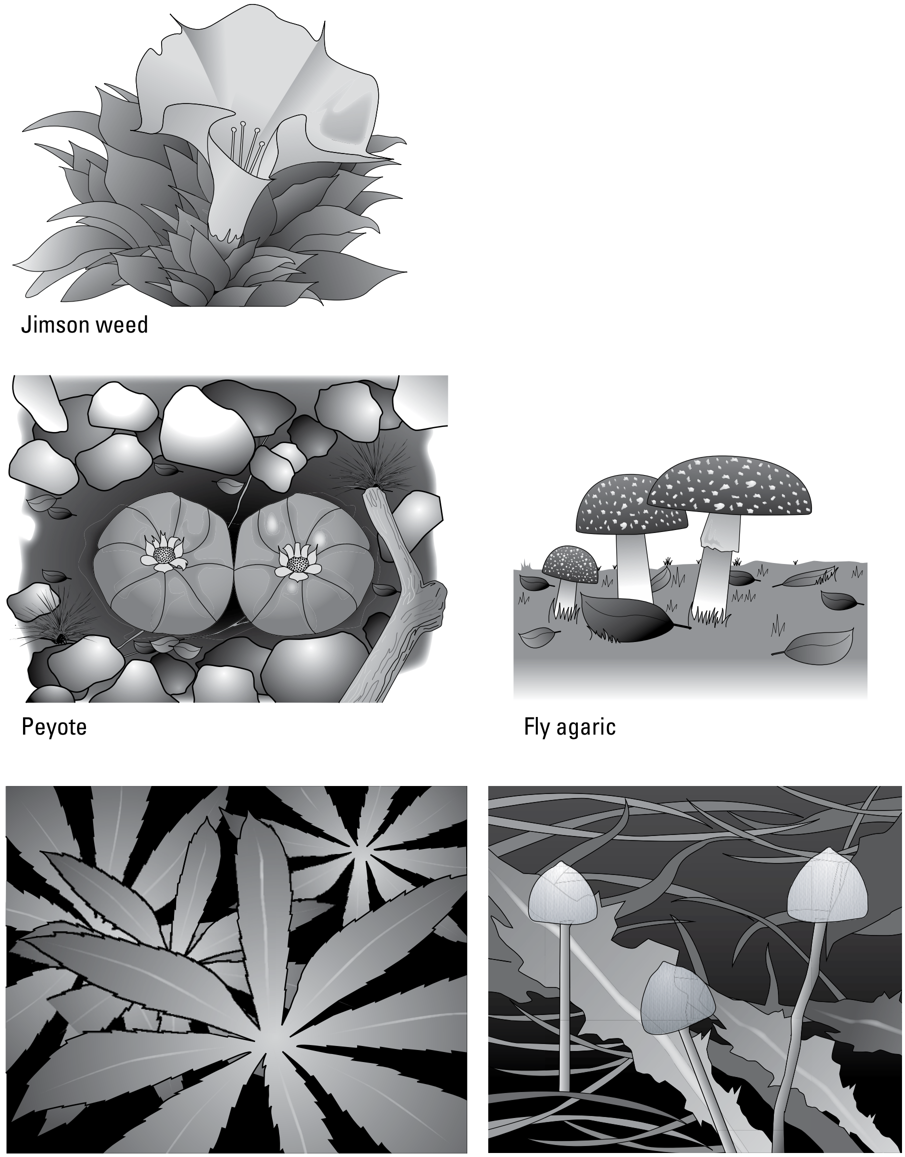
Having visions: Hallucinogenic plants

Many cultures and religions around the world use hallucinogenic plants, also called psychoactive drugs, in their rituals. Priests, shamans, and other spiritual leaders use hallucinogens because they think the altered state of mind helps them contact spiritual beings. Some churches use psychoactive drugs as part of their rituals. And some people take hallucinogenic drugs for recreational use.

REMEMBER

Hallucinogens, or psychedelics, are chemicals that alter a person's perception of reality. They can also affect a person's mood or thoughts. Figure 18-5 shows some plants that people use to alter their mental state:

- Peyote is a small, spineless cactus, with the scientific name *Lophophora williamsii*. Peyote contains the chemical mescaline. After the peyote is ingested, people often initially feel slight nausea. In addition to altered perceptions, mescaline causes increased heart rate and blood pressure.
- The fly agaric, or *Amanita muscaria,* isn't a plant at all; it's a fungus. It produces the hallucinogenic chemicals muscimol and ibotenic acid. These chemicals inhibit certain neurons in the brain and, in small doses, can produce feelings of euphoria, hallucinations, and drowsiness. Many people who eat these mushrooms fall into a deep sleep.



Jimson weed

Peyote

Fly agaric

Marijuana

Magic mushrooms

FIGURE 18-5: Hallucinogenic plants.

- Marijuana, or *Cannabis sativa,* has many names: mary jane, pot, weed, ganja, and grass, just to name a few. Marijuana's mood-altering effects are caused by the chemical delta-9-tetrahydrocannabinol, or THC for short. Marijuana can be smoked or eaten in order to take THC into the body. THC passes from the lungs or digestive system to the blood and then to the brain and other organs. In the brain, THC binds to cells that have the right receptor for it. Receptors for THC are highest in the areas of the brain that influence pleasure, memory, thinking, concentration, sensory and time perception. (Some varieties of *C. sativa* are bred for lower levels of THC, and higher levels of a chemical called cannabidiol or CBD. Doctors prescribe CBD to prevent some types of epileptic seizures, and many people use it to get relief from pain. Scientists are currently still researching whether CBD is effective at reducing anxiety. People also use varieties of *C. sativa* that are low in THC as a source of the fiber hemp, as discussed earlier in this chapter.)

- Magic mushrooms, or mushrooms in the genus *Psilocybe,* produce the chemicals psilocybin and psilocin. After eating magic mushrooms, people often go through a period of intense yawning, followed by hallucinations and an increased heart rate. The chemicals in these mushrooms have a structure similar to the neurotransmitter serotonin, leading to stronger and longer serotonin signals in the brain.
- Black henbane, *Hyoscyamus niger,* is related to deadly nightshade and jimson weed. It produces similar alkaloid toxins, including atropine as well as hyosyamine. The difference between the toxicity of henbane and belladonna is mostly in the dose — henbane contains about ten times less the concentration of these chemicals. In the Middle Ages, Germans used to include henbane, called bilsen, as an ingredient in beer. Bilsen became pilsen over time, but is no longer included in pilsen beer because of its toxicity. People who thought they were witches may have spread a salve containing belladonna and henbane on their skin, causing them to have visions of flying in the air.
- Mandrake, or *Mandragora officinarum,* is famous because of its weird looking roots that people thought looked like, well, people. In the Middle Ages, many people believed in the Doctrine of Signatures, which said that the way a plant looked gave a clue to its medicinal uses. So, mandrake, which had roots that looked like the human body, was supposed to cure just about everything. People also believed that when you picked mandrake, the screams of the roots could knock a person out. Legends about mandrake persisted for centuries and even made it into the Harry Potter books. Like its relatives, belladonna and black henbane, mandrake produces alkaloids like hyoscyamine, atropine, and scopolamine. Like black henbane, people who believed they were witches used mandrake in their potions, probably resulting in hallucinations.
- Kwashi, which scientists call *Pancratium trianthum,* is used by the bushmen in Botswana. To induce visual hallucinations, the bushmen rub the bulb of the plant over cuts in their scalp. The active chemical in kwashi isn't known, but some relatives of kwashi produce alkaloids.

IN THIS CHAPTER

- Becoming Farmers
- Harnessing natural selection
- Engineering plants

Chapter 19

Foraging, Farming, and Engineering Plants

People have been cultivating plants for more than 12,000 years, which just goes to show how important plants are to people. Over those years, we've shaped their evolution to suit our needs. As the human population continues to grow, we need to figure out how to meet the increasing demand for food. This chapter looks at the use of plants in agriculture and explores how people are looking for new, more sustainable ways to support the human population.

From Foraging to Farming

What did you eat today? How many foods do you normally consume that come from plants? Chances are, much of what you eat comes from plants and, in particular, from flowering plants.

REMEMBER

Eighty percent of the calories that humans eat come from six flowering plants: wheat, rice, corn, potatoes, cassava, and sweet potatoes. These plants have been staples in the human diet for thousands of years, ever since people first started farming.

Exploring the origins of agriculture

Early humans were hunter-gatherers, moving around as they hunted wild animals and gathered wild plants from their environment.

REMEMBER

About 12,000 years ago, humans shifted from hunting and gathering to agriculture.

As people became farmers, they settled into communities that stayed in one place. The structure of these communities became the basis for modern civilization as it exists today. Historians say that the stable food supply supported population growth. As people stayed together in groups, they began to take on different roles in the community and specialized in certain trades. These changes led to the development of the world's first cities.

Some of the earliest agricultural sites are located in the *Fertile Crescent*, an area in the Middle East that follows the Nile, Tigris, and Euphrates rivers, forming a broad semicircle at the northern end of the Red Sea. The ancient civilizations of Egypt, Phoenicia, Assyria, and Babylonia farmed in this area, which today includes Egypt, Israel, Lebanon, and portions of Jordan, Syria, Iraq, Turkey, and Iran.

The first plants to be cultivated were probably wild plants that people had previously gathered. Figure 19-1 shows a world map marked with the kinds of plants that were first grown by early farming communities around the world.

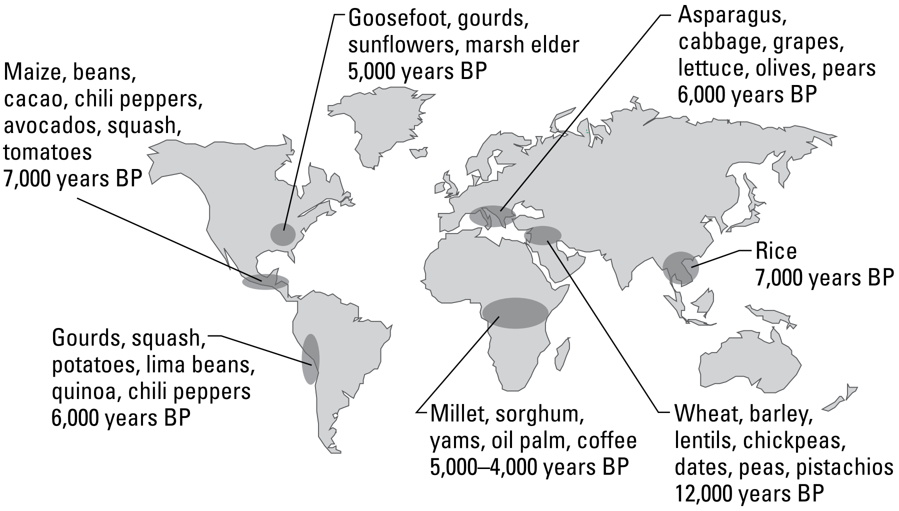

Maize, beans, cacao, chili peppers, avocados, squash, tomatoes 7,000 years BP
Goosefoot, gourds, sunflowers, marsh elder 5,000 years BP
Asparagus, cabbage, grapes, lettuce, olives, pears 6,000 years BP
Rice 7,000 years BP
Gourds, squash, potatoes, lima beans, quinoa, chili peppers 6,000 years BP
Millet, sorghum, yams, oil palm, coffee 5,000–4,000 years BP
Wheat, barley, lentils, chickpeas, dates, peas, pistachios 12,000 years BP

FIGURE 19-1: Origins of agriculture.

Some of the world's most important modern crops have been farmed since these early days:

- People first cultivated grains, such as wheat and barley, in the Fertile Crescent around 12,000 years BP (before present).
- The ancient Chinese started growing rice, which is also a grain, around 10,000 BP.
- Central Americans began farming the grain teotsinte, which is the ancestor of corn, around 9,000 BP. They also began growing beans and cacao, which is used to make chocolate, at least as early as 7,000 BP. (Thank you, ancient Central Americans!)
- Mediterranean people began cultivating olives around 6,000 BP.
- South American people were growing potatoes around 6,000 BP.
- Central Africans started farming coffee around 5,000 BP.

Using artificial selection to shape plant foods

As people domesticated their local wild plants, they began to change them. People chose the individual plants that had traits they liked best and bred them to create the next generation. Over time, this constant selection for certain traits led to crop plants that were significantly different from their wild cousins.

REMEMBER

Artificial selection, or selective breeding, is an evolutionary process in which humans choose individuals in a population that are allowed to reproduce based on their traits, leading to changes over time in the population. Artificial selection follows the same principles as natural selection (Chapter 11): the only difference is that human preference acts as the selection pressure.

One of the most famous examples of the power of artificial selection can be seen in a quick trip to your local grocery store. If you look around, you'll probably see several plants in the mustard family that appear quite different from each other — plants such as broccoli, cauliflower, kale, kohlrabi, and Brussels sprouts (see Figure 19-2). What you might not know is that these plants are all varieties of the same species, *Brassica oleracea*, and that their evolution from a wild mustard into their present forms was shaped by farmers. When farmers chose the mustards with the largest leaves generation after generation, they ended up producing kale. When they chose the mustards that had large, tasty flower clusters, they ended up producing broccoli. Farmers have used artificial selection for thousands of years to shape the appearance, flavor, and nutritional content of the foods we eat every day.

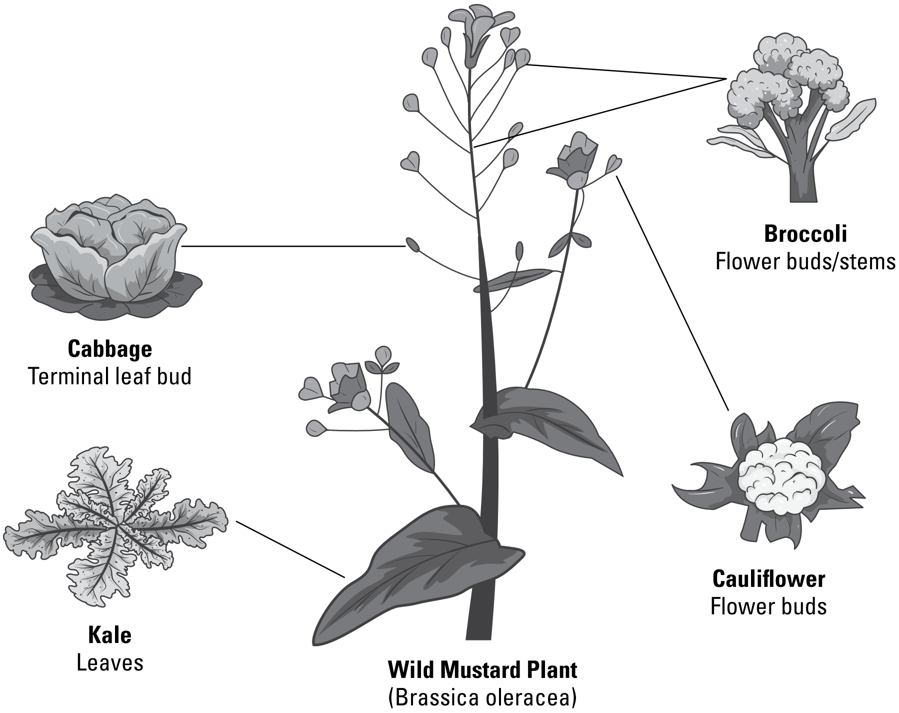


FIGURE 19-2: Artificial selection.

Keeping up with human population growth

Over eight billion people live on planet Earth today, and the number keeps increasing. According to the United Nations, 2.4 billion people experienced some food insecurity in 2022, with 900 million of those people experiencing severe food insecurity. The COVID-19 pandemic, war, and climate change are all disrupting food supplies and increasing the numbers of people who just don't get enough to eat. For the children of the world, lack of adequate nutrition often means death: over 3 million children a year die from hunger-related causes.

And although the number of people keeps growing, the Earth is staying the same size. More importantly, the amount of land that's usable as farmland remains the same size or may be decreasing due to soil degradation and desertification.

REMEMBER

Only about 3.5 percent of the Earth's surface is suitable for farming, and most of that is already being farmed. Humans use about 40 percent of the world's land surface, dedicating about 37 percent to agriculture. Of the area used for agriculture, one-third is used for food crops, and the rest is used for feed crops for animals or land for grazing.

To feed the growing human population, governments, scientists, and farmers are going to have to figure out how to get more food out of the land that's already being farmed.

People are already working on ways to come up with more food:

- **Eat less meat.** You have to feed a cow about 10–15 pounds of grain to make 1 pound of beef. Even though beef has more calories per weight than grains, you can still satisfy the caloric needs of a lot more people with 10–15 pounds of grain than you can with 1 pound of beef.
- **Produce a higher yield of crops from the land already in use.** Scientists and farmers have already demonstrated their abilities to increase yields through improvements in crop varieties, irrigation, fertilization, and pest control. (See the sidebar "The green revolution" for details.) During the years 1987 to 1996, for example, crop yields of soybeans and wheat in the United States doubled, and those of corn tripled. One way that scientists are trying to keep this trend going is by using genetic engineering to create genetically modified crop plants.
- **Find more *arable land,* which is land that's suitable for farming.** Unfortunately, even though the best land is already in use for farming, demand is so high that people are attempting to convert other land to farming, even if it's unlikely to be very successful. One of the biggest issues is the loss of forests, called *deforestation,* as people cut down trees to try and convert the land for farming.

  Cutting down forests for farming has many negative outcomes that outweigh the positives:

  - Forest land may not yield crops for very long, especially in the rainforest, where soils are shallow and nutrient-poor. Unfortunately, people do burn down parts of the rainforest in order to try and grow food. When their efforts fail a couple of years later, they move on and burn another piece.
  - Forests are important *carbon sinks:* Forests remove carbon dioxide from the atmosphere through photosynthesis and then use that carbon dioxide to build the mass of the trees. If forests are cut down or burned, the stored carbon in the trees can gets released back to the atmosphere as carbon dioxide, increasing the global temperature.
  - Forests are home to a great diversity of plants and animals. Not only are forests necessary to other kinds of life, they also harbor a great deal of the planet's biodiversity. Many useful products come from forests, and many more might be there waiting to be discovered.

THE GREEN REVOLUTION

In the 1940s, the world's population was growing rapidly at a faster pace than agriculture was producing food. Realizing that something needed to be done to meet the growing demand, private foundations and national governments from resource-rich nations started programs to improve farming in developing nations. For example, the Rockefeller Foundation in the United States funded a program to improve wheat yields in Mexico. The program, led by Norman Borlaug, spent almost 20 years using plant breeding to produce dwarf wheat varieties that gave a high yield and were resistant to plant pests and diseases.

In the 1960s, Borlaug was part of a group that brought the high-yield wheat to India and Pakistan and taught the farmers how to grow it to get the best results. In the 1980s, China adopted these improved agricultural varieties and practices, resulting in its growth into one of the leading food producing countries in the world. The improvements in food production as a result of the agricultural advances spearheaded by Borlaug were so dramatic that in 1968, the USAID director called it a "green revolution." Borlaug is credited with being the father of this revolution and with helping to save over a billion people from starvation. For his contributions to world peace by increasing food supplies, Borlaug received the Nobel Peace Prize in 1970.

- **Try new farming methods.** Scientists and farmers are testing new methods for producing food more efficiently. The methods include farming without soil by growing plants in tanks of water and nutrients (*hydroponics*) or by spraying a nutrient mist directly onto plant roots (*aeroponics*). Soil-free farming methods can be combined with *vertical farming*, in which layers of plants are stacked vertically, maximizing space utilization. Other farmers are finding ways to maximize available space by partnering with urban planners to create rooftop gardens in cities.

Speeding Things Up By Engineering Plants

Humans have been using artificial selection to guide the evolution of plants and animals for thousands of years, leading to many desirable changes in agricultural species. This method takes many generations to produce results, which may be safer but not fast enough for today's changing times. Over the last 50 years, scientists have developed new technologies that allow us to make direct changes to the DNA of organisms, vastly increasing the speed at which we can alter the traits of an organism.

REMEMBER

Genetically modified organisms (GMOs), which are also sometimes called *genetically engineered organisms*, are organisms whose genetic code has been changed in a way that does not occur naturally by mating or natural recombination.

Scientists have many reasons for using genetic engineering to alter the traits of organisms:

- Animals used in agriculture may be genetically engineered to make them grow faster, produce more milk, make leaner meat, or release human pharmaceutical products into their milk.
- Crop plants may be genetically engineered to be more resistant to diseases, insects, or weed killer, or to make additional vitamins.
- Bacteria and viruses may be altered to make them less harmful to people so that they can be used in vaccines.
- Bacteria can be genetically engineered with human genes so that they make human proteins that can be used as medicines.

At least some of these goals seem beneficial to humanity. Still, people have many questions and concerns about the safety of these efforts. Genetic engineering allows agricultural scientists to do almost immediately what it used to take traditional breeding programs decades to achieve. People wonder if these scientists are moving too fast, if they've really looked at all the possible consequences of creating GMOs.

Several characteristics of plants make it easy for scientists to genetically modify them:

- Plant cells and tissues can be grown in media in the lab.
- Pieces of DNA can be introduced into plant cells:
  - A bacterium called *Agrobacterium tumefaciens* (crown gall bacteria) infects plants, naturally introducing a piece of DNA into plant cells in the process.
  - Scientists use *gene guns* to shoot small pieces of metal that are coated with DNA into plant cells.
- Scientists can use hormones to induce clumps of plant cells to differentiate into complete plants.

Culturing plant tissues

REMEMBER

Tissue culture is the process of growing tissues on growth medium in a lab. Figure 19-3 illustrates the process of growing plant cells in culture:

- Plant cells are taken from any part of the plant, although tissues taken near meristems usually grow the best.
- The pieces of tissue are placed on special growth media containing hormones that favor the growth of plant cells.
- The cells begin to grow and form an undifferentiated blob of cells called a *callus*.
- Hormones are added to the medium to cause the callus to grow roots and shoots, thus developing into a complete plant.

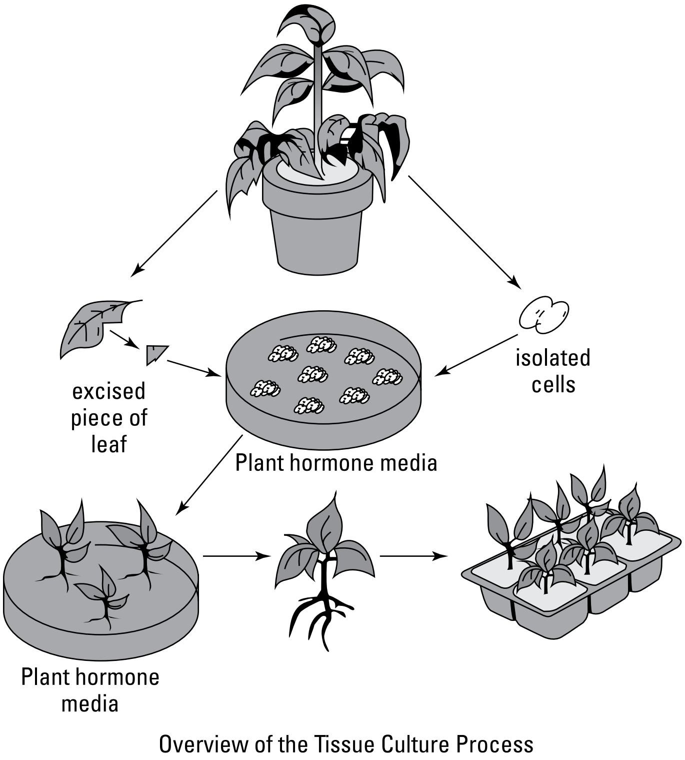

excised
piece of
leaf
isolated
cells
Plant hormone media
Plant hormone
media
Overview of the Tissue Culture Process

FIGURE 19-3: Plant tissue culture.

Transforming plants with Agrobacterium

REMEMBER

When *Agrobacterium* attacks plants, it transfers a small piece of DNA, called the *Ti plasmid*, into the plant cells.

Genes from the Ti plasmid insert themselves into the plant DNA, causing the plant cells to divide repeatedly, producing a lump of tissue called a gall at the crown of the plant where it enters the soil. The rapid cell division in the plant is very similar to the rapid cell division caused by cancer in animals.

Cutting DNA with restriction enzymes

Scientists use the unique talents of *Agrobacterium* to modify plant cells in order to insert specific genes into plant cells. To do so, the scientists first have to modify the Ti plasmid to carry the gene they want to put into plant cells, which is called the *gene of interest*. Scientists use enzymes called *restriction enzymes* to cut the DNA of the Ti plasmid and insert their gene. Restriction enzymes cut DNA at very specific sequences, and each restriction enzyme cuts at a unique sequence.

Figure 19-4 shows how restriction enzymes can be used to cut open the Ti plasmid, which is a circular piece of DNA. After the Ti plasmid is cut open, scientists can add their gene to the plasmid.

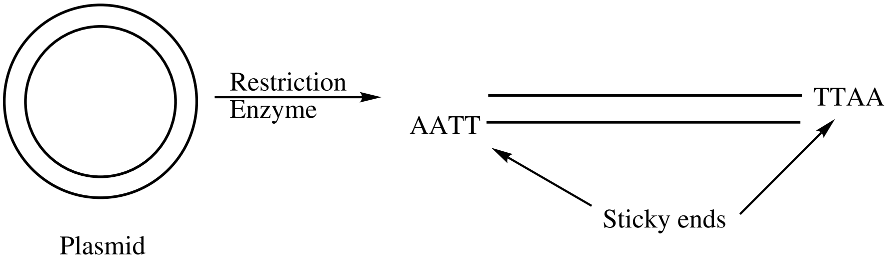


FIGURE 19-4: Restriction enzymes.

Inserting a gene into the Ti plasmid

Restriction enzymes make the process of cutting and combining pieces of DNA easy. To put their gene into the Ti plasmid, scientists follow these steps (see Figure 19-5):

1. **Choose a restriction enzyme that cuts DNA asymmetrically.**

   Restriction enzymes that cut the DNA backbone asymmetrically leave a piece of single-stranded DNA hanging off each end. These pieces of single-stranded DNA, called *sticky ends,* are complementary to other pieces of DNA cut with the same restriction enzyme and can form hydrogen bonds with them. For example, the sticky ends shown in Figure 19-4 have the sequences 5'AATT3' and 3'TTAA5'. A and T are complementary base pairs, so these ends could form hydrogen bonds and thus, stick to each other.

2. **Cut the gene of interest and Ti plasmids with the same restriction enzyme.**

   If you cut the Ti plasmid and the gene of interest with the same restriction enzyme, all the DNA fragments will have the same sticky ends.

3. **Combine the gene of interest and Ti plasmids.**

   The two types of DNA have the same sticky ends, so some pieces of plasmid DNA and the gene of interest will stick together. Thus, some plasmids will end up with a human gene inserted into the plasmid.

4. **Use an enzyme to seal the Ti plasmid closed again.**

   An enzyme called *DNA ligase* will form covalent bonds at the cut sites in the DNA, sealing together any pieces of DNA that combined together.

5. **Return the modified Ti plasmid to *Agrobacterium*.**

   When the bacteria and modified Ti plasmids are mixed together in a test tube, some bacteria will pick up the plasmid and move it into their cytoplasm. Scientists improve the chances of the bacteria picking up the plasmid by shocking them with alternating treatments of hot and cold temperatures.

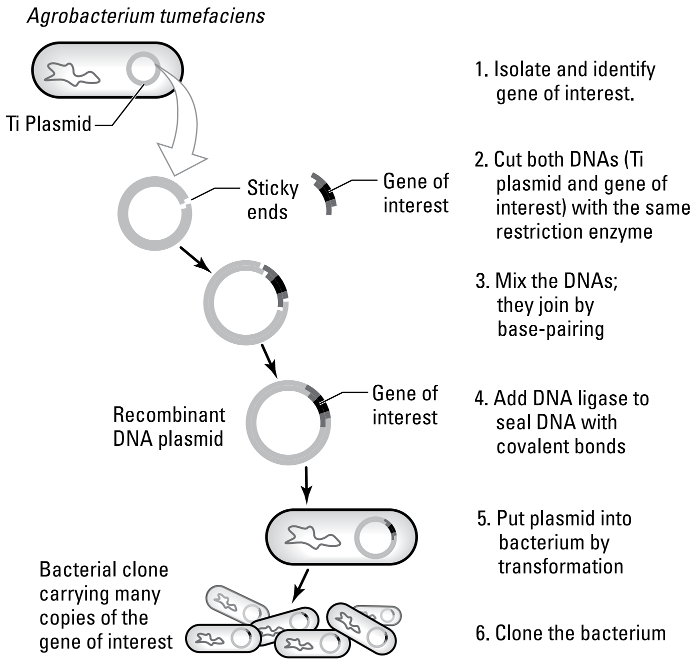

Agrobacterium tumefaciens
Ti Plasmid
Sticky ends
Gene of interest
Recombinant DNA plasmid
Gene of interest
Bacterial clone carrying many copies of the gene of interest
1. Isolate and identify gene of interest.
2. Cut both DNAs (Ti plasmid and gene of interest) with the same restriction enzyme
3. Mix the DNAs; they join by base-pairing
4. Add DNA ligase to seal DNA with covalent bonds
5. Put plasmid into bacterium by transformation
6. Clone the bacterium

FIGURE 19-5: Inserting a gene of interest into the Ti plasmid.

6. **Grow the bacteria and identify which ones picked up the plasmid.**

   When scientists modify the plasmid to add the gene of interest, they also add a gene to help them identify which bacteria have taken up the plasmid. Often, they add a gene that will make the bacteria resistant to antibiotics. Then when they grow the bacteria, they add the antibiotic to the growth medium. Only bacteria that took up the plasmid, gaining the gene of interest and the antibiotic resistance gene, will be able to grow.

Putting the Ti plasmid into plant cells

Figure 19-6 shows how scientists use *Agrobacterium* to create transgenic plants.

1. **Scientists punch out disks of leaf tissue from a plant and then combine the leaf disks with modified *Agrobacterium* that carries the gene of interest.**
2. **The bacteria infect the plant cells, transferring the Ti plasmid into the cells.**
3. **Genes move from the Ti plasmid into the DNA of the plant cells.**
4. **Scientists identify which plant cells have gained the gene of interest by looking for a chemical marker.**
5. **Scientists grow the modified plant cells in tissue culture.**
6. **Scientists use hormones to trigger the plant tissues to differentiate into new plants.**

   For more on which hormones would trigger root and shoot development, see Chapter 8.

REMEMBER

The new plants are genetically modified organisms because they contain the gene of interest inserted by the scientists. The plants contain this gene in every cell and will pass it on to their offspring when they reproduce.

Editing Plant Genomes

One of the newest developments in DNA technology is the development of *genome editing*, which enables scientists to make changes at very specific locations within an organism's DNA. Genome editing can be used to add, remove, or change specific genes.

REMEMBER

A *genome* is the complete set of DNA in an organism.

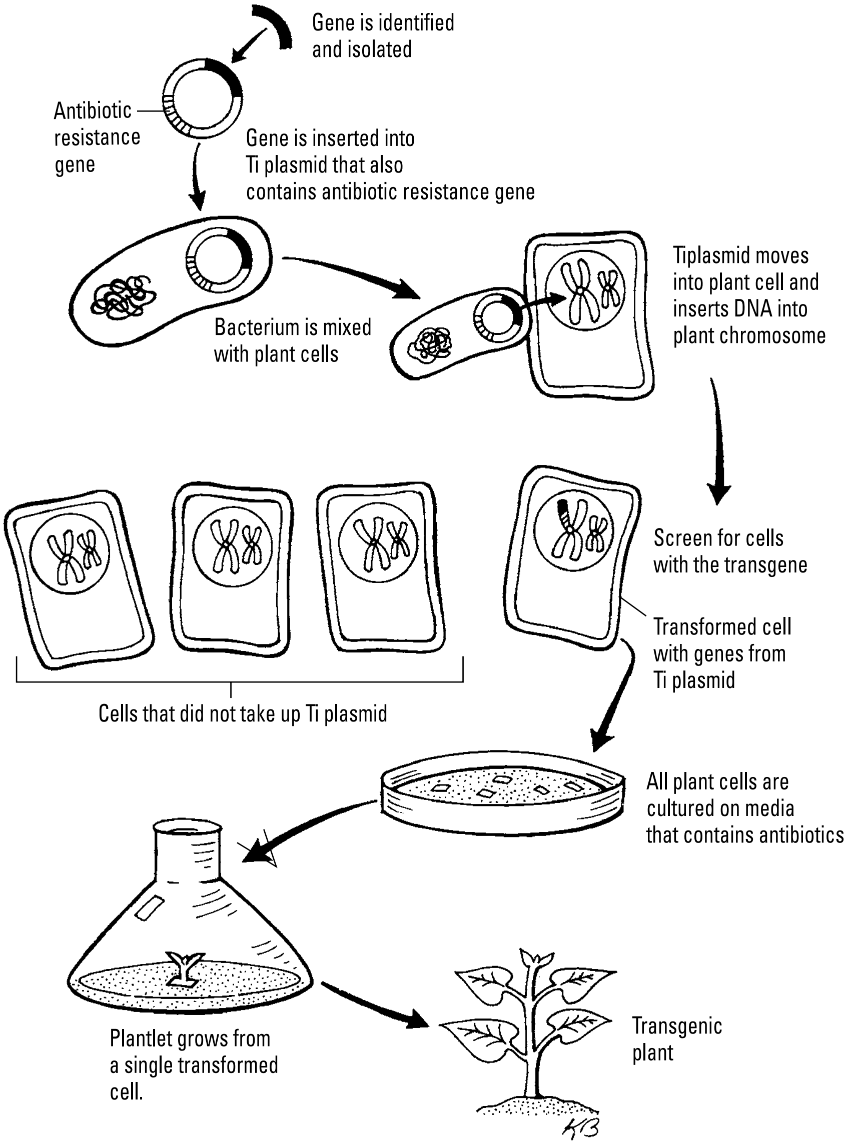

Gene is identified and isolated
Antibiotic resistance gene
Gene is inserted into Ti plasmid that also contains antibiotic resistance gene
Bacterium is mixed with plant cells
Tiplasmid moves into plant cell and inserts DNA into plant chromosome
Screen for cells with the transgene
Transformed cell with genes from Ti plasmid
Cells that did not take up Ti plasmid
All plant cells are cultured on media that contains antibiotics
Plantlet grows from a single transformed cell.
Transgenic plant
KB

FIGURE 19-6: Transforming a plant using *Agrobacterium.*

Genome editing became possible when scientists discovered a naturally occurring immune response inside bacterial cells called the CRISPR-Cas system (pronounced "crisper-cas"). Whenever viruses attack a cell that has CRISPR, the cell saves a piece of the viral genome, creating a sort of DNA library of past attackers. When the bacterial cell comes under potential attack again, it makes RNA copies of its saved viral genomes and uses them to scan the incoming genetic material. (Scientists call these RNA copies *crRNA* for *CRISPR-RNA.*) If the saved gene fragments match up with something in the new invader, defensive bacterial enzymes spring into action and chop out the bit of matching sequence, effectively disabling the virus. One of these defensive bacterial enzymes, called cas9, is shown in Figure 19-7.

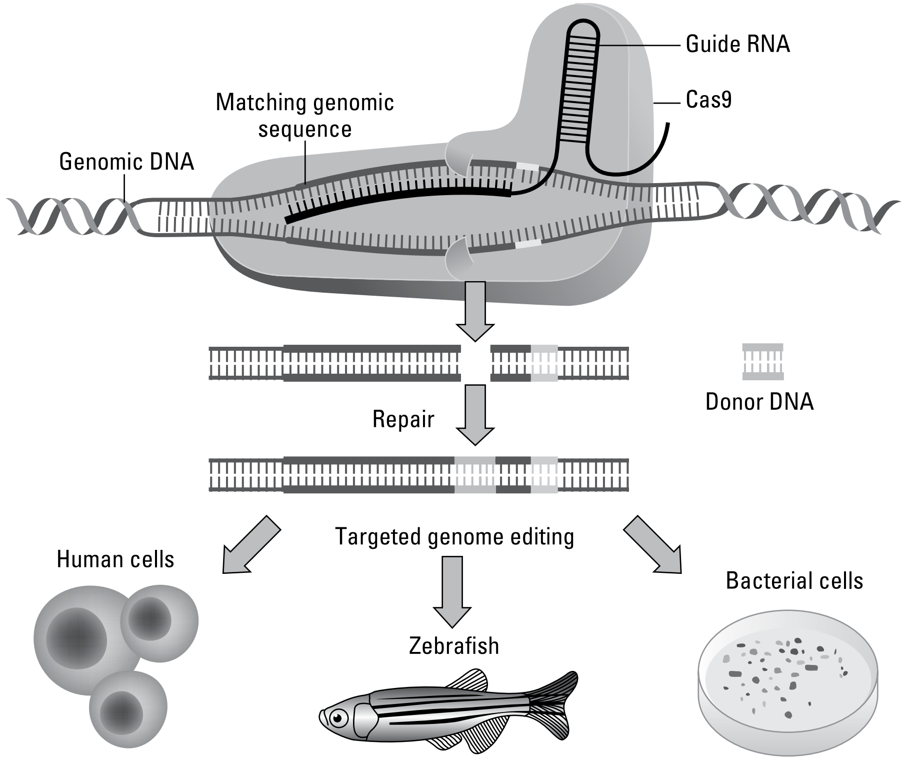

Guide RNA
Cas9
Matching genomic sequence
Genomic DNA
Donor DNA
Repair
Targeted genome editing
Human cells
Bacterial cells
Zebrafish

FIGURE 19-7: Editing genomes with CRISPR-Cas.

REMEMBER

For bacteria, the CRISPR-Cas system defends their cells against invading viral DNA. For some scientists, this system represented a highly specific gene targeting system.

Two brilliant scientists, Jennifer Doudna and Emmanuelle Charpentier, saw how cas enzymes use bits of crRNA to recognize viral DNA and wondered if they could teach those enzymes to recognize other genes as well. To make a long story short, they figured out how to make a *guide RNA* that a cas enzyme called cas-9 could use to search out specific locations in a genome. The guide RNA contains a short piece of RNA that has the ability to recognize a target DNA sequence (just like the crRNA can recognize viral genes). When the guide RNA finds its matching sequence in the genome, the cas enzyme cuts at that location (see Figure 19-7). Scientists can use this specific targeting system to change, insert, or remove DNA from a genome.

Even though genome editing is a relatively new technology, scientists are already testing its ability to make improvements in crop plants. In the first four years after CRISPR-Cas was used to modify plant genomes, scientists reported that it was used to modify 41 food crops, 15 industrial crops, six oil crops, eight ornamental crops, one fiber crop, and one feed crop! Although some of the resulting changes to crops were cosmetic, or favored industrial farming practices, many were intended to meet the nutritional needs of a growing human population or help plants protect themselves in a changing environment. Some of the more recent experiments include:

- Increase yield in rice and wheat by targeting hormone production.
- Lower gluten content in some varieties of wheat to benefit people with gluten intolerance.
- Increase starch content in some varieties of rice in order to increase calories and nutrition.
- Increase disease resistance in cocoa trees (see Chapter 18 for more info on this tree), rice, and wheat.

Trying to Build a Better World

People around the world are suffering from malnutrition. And, things could get a whole lot worse as the human population continues to grow, perhaps adding 100 million people per year for the next 30 years. Some scientists believe that they must use genetic engineering to improve agricultural crops to meet these needs and find ways of growing more crops, faster.

REMEMBER

Scientists are using genetic engineering to create new varieties of crop plants that are disease and pest resistant, better able to survive environmental extremes like cold and drought, more efficient at drawing nutrients from the environment, and more nutritious for people to eat.

Saving lives with golden rice

According to UNICEF, vitamin A deficiency increases the risk of 140 million children per year for illness, hearing loss, blindness, and even death. Scientists are trying to help these children by using genetic engineering to improve the nutritional content of white rice, which is a staple food in many countries.

REMEMBER

Biofortification is the creation of plants that make or accumulate additional nutrients.

If people eat provitamin A, or beta-carotene, it will convert to vitamin A in the body. Rice plants actually make provitamin A in their leaves, but not in the grain, which is what people eat. And people in rural areas of Asia and Africa often prefer white rice, which is especially nutrient-deficient, over the more nutrient-rich brown. However, scientists figured out that only two genes needed to be added to the rice plants to turn on provitamin A production in the grain. They used genetic engineering to add those two genes and created a strain of rice called *golden rice.* The grains of golden rice are yellow instead of white because they contain provitamin A, or beta-carotene, which is yellow-orange in color.

The Golden Rice Humanitarian Board is currently working to distribute golden rice varieties free of charge to farmers in countries where vitamin A deficiency is a problem. However, the situation is a complex one due to cultural, economic, and political factors. In 2021, the Philippines became the first country to approve the planting of golden rice, planning to focus on the provinces where vitamin A deficiency is most prevalent. However, anti-GMO activists brought the issue to court, resulting in a 2024 decision by the Philippines Court of Appeals to ban the growing of golden rice in that country.

Stopping crop pests with Bt

The larvae of moths and butterflies *(lepidopterans)* can do significant damage to crop plants. For example, the larva of the corn borer moth causes damage to corn leaves, stalks, and ears, reducing the yield of corn crops. One way to control lepidopterans is by using a toxin produced by the bacterium *Bacillus thuringiensis,* nicknamed *Bt.* The toxin produced by *Bt* targets the gut of leptidopterans, causing them to stop feeding and die. Many organic farmers use *Bt* to control lepidopterans by spraying the bacterium on their crops. When the larvae eat the toxin from the bacterium, they die.

Scientists have also used genetic engineering to make corn plants that make the bacterial toxin all by themselves. They removed the gene that's the blueprint for the toxin from the bacteria and then introduced it into corn plants, creating *transgenic Bt corn*. The corn plants use the bacterial gene to make the toxin. If larvae graze on these transgenic plants, they die. Farmers don't have to use pesticides or spray *Bt* to protect their crops. Scientists have also introduced the gene from *Bt* into cotton and soybean, as well as other crops.

Resisting Weed killers

Another problem that farmers face is the problem of weeds. The safest solution in terms of the environment is to pull them by hand, but this practice is extremely time-consuming. So, many farmers turn to weedkillers as a way to kill plants that are competing with crop plants for nutrients. One of the most common weedkillers in use is the chemical *glyphosate*, which is the active ingredient in weedkillers like Roundup. Some farmers will spray an entire field with glyphosate to kill all the weeds before planting the field with soybean or corn. Spraying a field to kill weeds is much easier than plowing the weeds into the soil.

Bayer (formerly Monsanto) introduced a gene that makes crop plants able to survive the application of Roundup. If farmers plant Roundup Ready crops, they can spray their fields with Roundup, killing all the weeds and leaving the crop plants behind. Currently available Roundup Ready varieties exist for soybean, corn, cotton, sugar beets, alfalfa, and canola.

The repetitive use of Roundup and other weedkillers on crop plants has some undesirable consequences, including increased resistance in weeds. By using Roundup over and over, farmers have consistently killed the susceptible weeds, leaving the most resistant weeds to survive. In some places, farmers are now having to deal with *superweeds* that Roundup can't kill.

Making drugs and commercial enzymes with biopharming

REMEMBER

Recently, companies have begun experimenting with *biopharming*, the process of engineering crop plants like corn to produce drugs and vaccines for use in medicine and enzymes for use in commercial processes. Scientists create *pharma crops* by introducing a gene for a drug or an enzyme into a crop plant like corn, rice, barley, or soybean. The plants are grown in open fields on farms. After harvest, the desired product is purified from the plant material.

The Canadian company Medicago used biopharming as part of their strategy to develop a vaccine against SARS-CoV-2 virus. They inserted a piece of the viral genome into *Agrobacterium*, then infected plants with the bacterium. The bacterium transferred the viral gene to the plants and the plants made the viral protein, which could then be used in the vaccine. (For a reminder on how to modify plants using *Agrobacterium*, refer to the section "Transforming plants with *Agrobacterium*" earlier in this chapter.)

Biopharming has the potential to lower the production cost of pharmaceuticals, making drugs available at cheaper prices and saving lives. The development of this technology faces many regulatory hurdles, however, in part because activists and many scientists are afraid of what might happen if these crops are grown in open fields. Pollen released from these crops may spread to other crop plants or to wild plants, transferring the genes for these products into other plants. People and animals may then end up eating foods that contain drugs, hormones, or commercial enzymes. Advocates for this technology say precautions can be taken to minimize this risk, for example, by using non-food plants as the hosts for the therapeutic genes.

Let's Talk, Talk, Talk about It: Pros and Cons of Genetic Engineering

The use of genetic engineering to alter living things is controversial for many reasons: People have questions about the benefits, safety, environmental impacts, financial rewards, and even the ethics of these practices. And yet the use of GMOs in agriculture is increasing to the point that it's getting hard to find foods, especially those that contain corn and soy that don't have a genetically engineered component. Many scientists have entered the debate about these products, examining the benefits and expressing concerns.

The pros of GMOs:

- Crop plants that resist weedkillers are easier to grow, which can increase crop yields and profits for the farmer.
- Crop plants that resist agricultural pests may reduce the need for pesticide use, protecting the environment from their effects, decreasing costs for the farmer and producing higher yields.
- If crop plants or farm animals raised for human consumption are given genes to improve their nutrition, people could be healthier.
- If farm animals raised for human consumption are given genes to increase their yield of meat, eggs, and milk, then more food may be available for the growing human population, and these greater yields may also increase profits for farmers.
- Medicines and vaccines produced in pharma crops may be cheaper and more available to the human population.
- If the human population continues to increase without changes to current agricultural practices, food insecurity will continue to increase.

The no's of GMOs:

- Engineered crops may pollinate other crops or wild relatives, transferring the introduced genes into the food supply in an uncontrolled fashion. After these genes have been transferred, it would take a rigorous surveillance system to track down all the affected plants and remove them from the human food supply.
- The profits of GMOs mostly go to the companies that develop them, not to farmers or consumers. Companies patent the engineered organisms they develop and carefully control the seed supply. Farmers must purchase new seed each year and aren't allowed to save seed from a crop as that is considered copyright infringement. If a small farmer can't afford to buy the engineered crop, he must compete with farmers who can, potentially making it harder for small farms to stay in business.
- Scientists question whether GMOs are necessary and if they represent the best way to solve agricultural problems. GMOs may introduce as many agricultural problems as they solve. And typically, agricultural biotechnology doesn't encourage sustainable farming practices because, to be profitable, companies develop products that must be purchased over and over again.
- Animals that are engineered to produce more milk, eggs, or meat may be at greater risk for health problems.
- Genetic modification of foods may introduce allergens into foods, and current labeling in some countries may not be sufficient to protect the consumer

More and more GMOs are entering the human food supply. The big agricultural firms that produce these products make a great deal of money and are active supporters of this technology. Personally, I don't think we should "just say no to GMO" and throw out the good with the bad. If GMOs can deliver vitamins to malnourished children or vaccines to those at risk for disease, then the benefits of those products outweigh the risks. However, I'm not personally in favor of genetic modifications that encourage unsound environmental practices, large scale farming of limited crop species, or cruelty to animals. We need to continue to discuss these issues as a society and weigh the pros and cons of each situation. In these debates, some important questions to ask are "What are the risks versus benefits?," "Who benefits?," and "Who is put at risk?"

IN THIS CHAPTER

- » Mastering the fundamentals of ecology
- » Investigating plant interactions
- » Exploring plant communities

Chapter 20

Making Connections with Plant Ecology

Plants are an incredibly important part of life on Earth. Plants make the food upon which all organisms rely. They provide homes to many other species, and they are part of the structure of ecosystems. This chapter covers the fundamental principles that underlie the interactions between all species and explores the importance of plant communities in the environment.

Exploring Ecosystems

All life on Earth is interconnected — organisms depend on each other for food and are impacted by each other's actions. Life depends on the environment, too for water, light, minerals, and a place to live.

REMEMBER

An *ecosystem* is a group of living and nonliving things interacting with each other in a particular environment. Ecosystems can be large or small, from the entire web of life interacting with each other and the surface of the Earth, called the *biosphere,* to a tiny ecosystem in a tide pool along the seashore.

Whatever its size, every ecosystem includes certain components:

- ***Abiotic factors* are the nonliving parts of the ecosystem.** Abiotic factors include things like sunlight, water, soil, air, and the remains of dead organisms.
- ***Biotic factors* are the living components of the ecosystem.** Scientists organize the biotic factors of ecosystems into categories (shown in Figure 20-1):
  - *Organisms* are the living things that function as individuals. You are an organism, as is a tree.
  - *Populations* are groups of the same species living in the same place. A forest, for example, may include a population of oak trees, a population of salamanders, and a population of squirrels. Even very similar organisms are considered different populations if they aren't the same species.
  - *Communities* are groups of one to many species that live in the same place. All the populations of different species that live in the same forest make up the forest community.

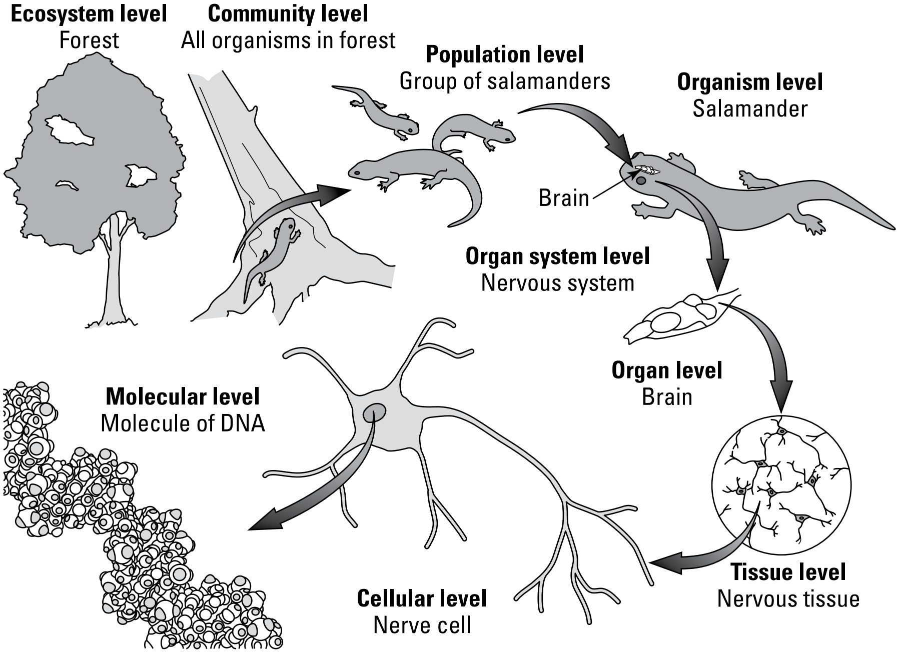

Ecosystem level
Forest
Community level
All organisms in forest
Population level
Group of salamanders
Organism level
Salamander
Brain
Organ system level
Nervous system
Organ level
Brain
Molecular level
Molecule of DNA
Tissue level
Nervous tissue
Cellular level
Nerve cell

FIGURE 20-1: The organization of living things.

Scientists who study ecosystems, called *ecologists*, are interested not only in the components of the ecosystem, but also in how all the components interact with each other. *Ecology* is the study of how organisms interact with each other and their environment.

Figuring out your job description

Every species in an ecosystem plays a certain role in that system — it lives in a certain area, uses resources, and either eats or is eaten by other species.

REMEMBER

The particular role a species plays in an ecosystem — including where it lives and which resources it uses — is called its *ecological niche*. The particular place where a species lives is its *habitat*.

All organisms need food because it provides the energy and matter necessary for growth, repair, and reproduction. One way of separating organisms is by the method they use to get food. How an organism gets its food is a big part of its niche. Ecologists commonly divide the organisms in an ecosystem into three categories, called *trophic levels*, based on how they get their food:

- ***Producers* make their own food.** Plants, algae, and photosynthetic bacteria are all producers that use energy from the sun to combine carbon dioxide and water, forming carbohydrates by the process of photosynthesis (for more on how they do this, flip back to Chapter 5). Producers can also be called *autotrophs*.
- ***Consumers* eat other organisms.** Consumers can be further divided based on what type of organism they eat.
    - *Primary consumers* eat producers. Because producers are mainly plants, primary consumers are also called *herbivores* (plant-eating animals).
    - *Secondary consumers* eat primary consumers. Because primary consumers are animals, secondary consumers are also called *carnivores* (meat-eating animals).
    - *Tertiary consumers* eat secondary consumers, so they are also carnivores.
- ***Decomposers* break down dead matter.** True decomposers, such as bacteria and fungi, release enzymes onto dead matter, breaking it down into solution, and then absorbing it as food. (For more on the fungal way of life, head to Chapter 17). Other organisms, such as scavengers and detritivores, also eat dead matter, but they ingest larger pieces and break them down internally. Scavengers, such as crabs and vultures, often feed on the remains of carcasses left by consumers, while detritivores, such as worms, ingest small pieces of *detritus*, the collection of random dead matter in an ecosystem.

Going with the flow of energy

Plants and other photosynthetic organisms are fundamental to most ecosystems on Earth because they can capture energy and matter from the environment and store it in food molecules. All other organisms in an ecosystem ultimately rely upon the food made by plants and other autotrophs. Primary consumers eat plants, then secondary consumers eat primary consumers, and so on, creating *food chains,* such as the one in Figure 20-2, that show how each organism gets its food.

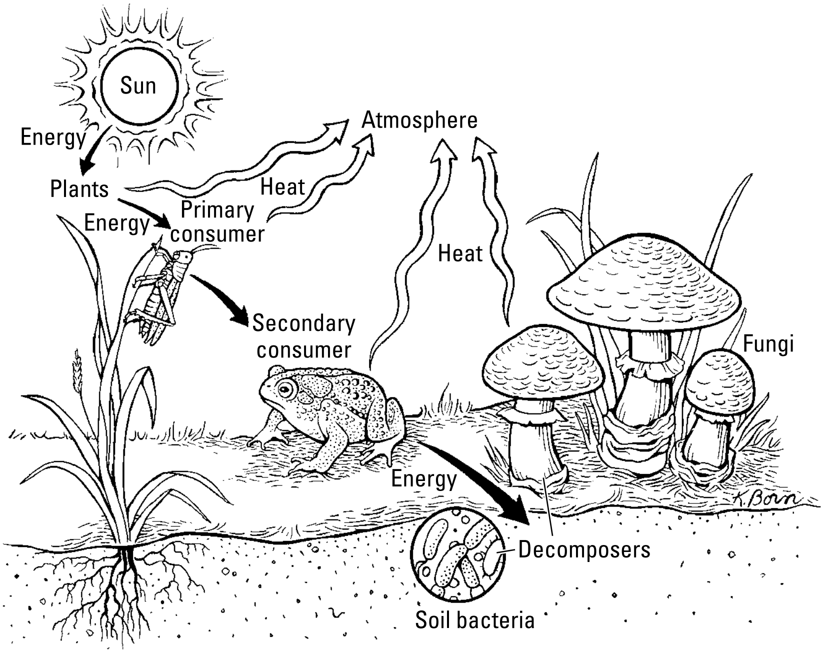


FIGURE 20-2: Energy flow in ecosystems shown through a food chain.

In an ecosystem, food chains branch and intersect with each other to create a complex web of interactions called a *food web.* Food chains and food webs show the flow of energy and matter through the different trophic levels of an ecosystem.

Living by the laws of energy

The sun is the ultimate source of energy for almost all life on Earth — without the energy from the sun, life on Earth just couldn't exist. Energy from the sun is captured by plants and other producers that make the food for all living things. Even the types of energy that humans rely upon, such as electricity and gasoline, can ultimately be traced back to the sun. For example, most of the oil and coal people rely upon today were made from the remains of plants that grew some 350 million years ago during the Carboniferous period. The sun radiates a constant flow of energy upon the Earth, and plants are first in line to capture it and make it usable for life. Understanding the movement of energy from the sun through ecosystems will be much easier if you know a few rules about the nature of energy.

Four important energy principles form the foundation of interactions in ecosystems:

- **Energy can't be created or destroyed.** This statement represents a fundamental law of the universe, called the *first law of thermodynamics.* The consequence of this law is that every living thing has to get its energy from somewhere; they can't make it for themselves. Even plants, which make their own food, can't make their own energy — they capture energy from the sun and store it in the food they make.
- **When energy is moved from one place to another, the energy is *transferred.*** When a primary consumer eats a producer, the energy that was stored in the body of the producer is transferred to the primary consumer. When describing energy transfers, be sure to say where the energy is coming from and where it's going to.
- **When energy is changed from one form to another, the energy is *transformed.*** When plants photosynthesize, they absorb light energy from the sun and convert it into the chemical energy stored in carbohydrates. So, during photosynthesis, light energy is transformed into chemical energy. When describing energy transformations, be sure to state the form of energy before and after the transformation.
- **When energy is transferred in living systems, some of the energy is transformed into heat energy.** This statement is one way of representing another law of the universe, called the *second law of thermodynamics*. The impact of this law on ecosystems is that no energy transfer is 100 percent efficient. After energy is transformed to heat, it's no longer useful as a source of energy to living things.

Stacking up the costs of energy transfer

Energy from the sun transfers through the trophic levels of food webs, supplying living organisms with the energy they need. However, the amount of energy that's available to life decreases as it moves through the trophic levels. Every organism constantly transfers energy for its own needs, and every energy transfer comes with a cost of energy that's transferred to the environment as heat. As an example, think about your own body as you exercise — you heat up and begin to sweat. Your body heats up from the all the energy transfers your cells are doing in order to provide energy to your muscles. The heat energy then transfers to your skin and out to the air around you. This example is pretty dramatic — you can actually feel the heat radiating off a person who has been exercising — but the same thing is going on all the time, in your body and in the bodies of living things all around you. Even plants, which can't get up and run around, are constantly doing energy transfers inside their cells, causing some energy to become heat that's then released to the environment.

So, if the organisms in each trophic level use some of the energy they capture for their own functions, causing some of the energy to be released as heat to the environment, then the total amount of energy available as you move through the trophic levels becomes less. This decline in the amount of available energy can be represented by an *energy pyramid*, also called a *trophic pyramid*. Energy pyramids like the one in Figure 20-3 show how the available energy decreases as it moves through the trophic levels in an ecosystem:

- **Producers capture about 1 percent of the energy available from the sun and store it in the molecules that make up their bodies.** As producers transfer energy for growth, some energy is also transferred to heat that's released to the environment. Ultimately, most of the energy that enters our ecosystem from the sun returns to space as heat.
- **Primary consumers get about 10 percent of the energy that was originally captured by the producers they eat.** Remember that most of the captured energy was released to the environment as heat during energy transfers as the producers grew. As primary consumers transfer energy for growth, they also release most of the available energy to the environment as heat.
- **Secondary consumers get about 10 percent of the energy that was captured by the primary consumers.** Secondary consumers eat primary consumers, using the molecules from their bodies as food. Again, as secondary consumers transfer energy for growth, some energy is also transformed to heat that's released to the environment.
- **Tertiary consumers get about 10 percent of the energy that was captured by the secondary consumers.** Tertiary consumers eat secondary consumers, transfer energy for growth, and transform some energy to heat that's released to the environment.
- **Decomposers use the dead matter from every level of the pyramid as their source of food.** As organisms die and some of their remains become part of the environment, decomposers use these remains as their source of energy and matter for growth. Decomposers transfer energy in the same way as other types of organisms.

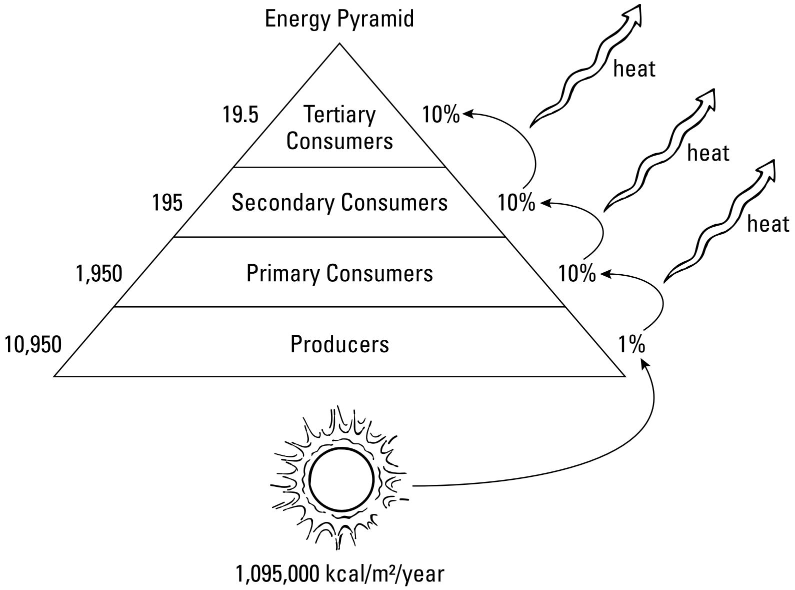


FIGURE 20-3: The energy pyramid (trophic pyramid).

REMEMBER

Ecologists say that energy flows through ecosystems. Energy enters ecosystems from the sun, passes through the bodies of living things, and then flows back out into the environment as heat released to the atmosphere. Ultimately, all the heat released by the bodies of organisms is transferred from the atmosphere back out to outer space.

You may have heard of organisms that are *top predators* — in other words, the organism at the top of a food chain. Top predators usually do not go beyond the level of tertiary consumers because the amount of energy available to support life becomes less as you move up the energy pyramid. Past the tertiary consumer level, too much energy has been depleted from the system to support higher trophic levels.

REMEMBER

The amount of energy at each trophic level in proportion to the next trophic level is called *ecological efficiency*. Although the percentage of energy passed from one level to the next can vary, ecologists use the *10 percent rule*, which represents an estimated 10 percent energy transfer from one trophic level to the next.

WARNING

You may hear people, even scientists, say that "energy is lost" or "energy is lost as heat." These statements can be confusing because they make it sound like energy disappears somehow. But you know from the first law of thermodynamics that energy can't be destroyed or disappear. The correct interpretation of statements like these is that useful energy is lost from the system as it is transformed into heat. In other words, once energy is transformed to heat, organisms in an ecosystem can't use it as a source of energy for growth. So, a scientist, even your teacher, may say something about energy being lost. They probably know what they mean, but it may get confusing for you. So, take my advice and never use the words lost, disappear, destroyed, or created when you're talking about energy. Use the words transfer and transformed instead, and you'll avoid a great deal of confusion.

Going round and round with matter cycles

Almost all the matter on planet Earth today, including the molecules that make up your body and the bodies of the living things all around you, has been here since the Earth first formed. Think about it — energy constantly comes in from the sun, but the Earth isn't constantly being bombarded with asteroids. So, where do living things get the raw materials to build their bodies? By recycling! All the carbon, hydrogen, oxygen, nitrogen, and other elements that make up the molecules of living things have been recycled over and over throughout time. When decomposers break down the bodies of dead organisms, they release atoms back to the environment in forms that other living things can use.

REMEMBER

Ecologists say that matter cycles through ecosystems. Scientists track the recycling of atoms through cycles called *biogeochemical cycles* (*bio-* because the recycling involves living things, *geo-* because it involves the Earth, and *chemical* because it involves chemical processes).

The carbon cycle

Life on Earth is made of carbon — the proteins, carbohydrates, and fats that make up the bodies of living things all have a carbon backbone. Carbon becomes available to ecosystems when producers, such as plants, capture it from the atmosphere as carbon dioxide (CO_2), using it to build carbohydrates in the process of photosynthesis. (For the details on photosynthesis, check out Chapter 5.) Producers capture carbon and incorporate it into food molecules in a process called *carbon fixation*. Once producers produce food molecules, organisms recycle the carbon through ecosystems, moving it through food webs and back to the atmosphere, forming a pathway of carbon called the *carbon cycle*. Figure 20-4 presents the key processes that transfer carbon through the carbon cycle:

- **Producers fix carbon from the environment and incorporate it into food molecules.** Most ecosystems rely upon producers such as plants to fix carbon using photosynthesis. During the process of photosynthesis, plants make glucose ($C_6H_{12}O_6$) out of carbon dioxide (CO_2). Plants then use the food they make as a source of matter to build the molecules that make up their own bodies.
- **Consumers and decomposers eat other organisms, transferring carbon into their own bodies.** Consumers and decomposers mostly take in proteins,

carbohydrates, and fats from their food. Then, they rearrange the molecules from their food into the molecules they need for their own bodies.

- **When all living organisms break down food molecules for energy, they release carbon back to the environment as carbon dioxide.** Many organisms use cellular respiration to break down food molecules and transfer the energy from food to ATP for use in cellular processes. When food molecules are broken down to allow energy transfer, cells rearrange the bonds in the molecules, forming carbon dioxide (CO_2) and water (H_2O) as waste. These molecules have very little available energy, so cells release them back to the atmosphere as waste.

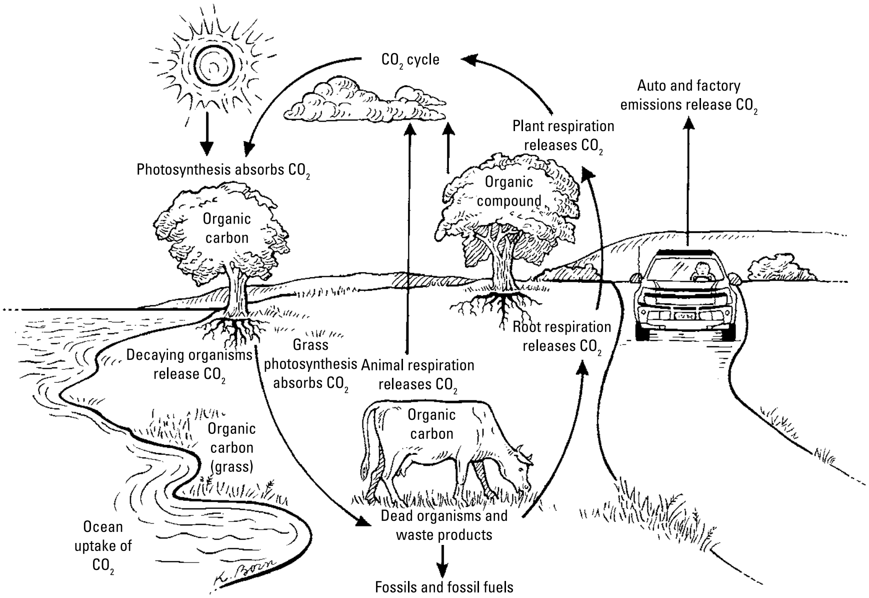

CO_2 cycle
Auto and factory emissions release CO_2
Plant respiration releases CO_2
Photosynthesis absorbs CO_2
Organic compound
Organic carbon
Root respiration releases CO_2
Grass photosynthesis absorbs CO_2
Animal respiration releases CO_2
Decaying organisms release CO_2
Organic carbon (grass)
Organic carbon
Dead organisms and waste products
Ocean uptake of CO_2
Fossils and fossil fuels
K. Born

FIGURE 20-4: The carbon cycle.

WARNING

The most common mistake people make when they try to trace the movement of carbon through ecosystems is they forget that most of the carbon enters the ecosystem as CO_2 from the atmosphere. Gaseous CO_2 is invisible, and it's hard to imagine that something invisible can be used to build an organism like a giant redwood tree. Most people focus on what they can see, and they imagine that when organisms die, their molecules return to the soil, and then trees absorb the carbon along with water through their roots. This idea is mostly incorrect. Yes, plants absorb water and minerals through their roots, but they don't get carbon from the soil. And when organisms die, their molecules don't get stored in the soil. Dead bodies get eaten by fungi and bacteria who use the molecules to build their own cells. The decomposers do cellular respiration, releasing CO_2 back to the atmosphere, where plants can grab it again during photosynthesis.

As carbon cycles through ecosystems, the balance of carbon can shift between locations.

Carbon sinks store carbon, whereas *carbon sources* release carbon to the environment. Carbon sinks can store carbon in the environment for long or short periods of time:

- The bodies of living organisms store carbon for relatively short periods of times.
- Fossil fuels contain carbon that was stored in the bodies of living organisms long ago and then trapped in a way that the proteins, carbohydrates, and fats were converted to coal, oil, and natural gas deposits.
- The world's oceans store large amounts of carbon dioxide dissolved as gas in the water.
- Mineral forms of carbon, such as calcium carbonate, store carbon in the shells of some living things. Fossil shells can also store significant amounts of carbon, like those that make up the White Cliffs of Dover in England.

Human activities, particularly those since the Industrial Revolution, are having a big impact on the global carbon balance.

- **When people cut down forests, a process called deforestation, they eliminate carbon sinks.** In addition, if the wood is burned, the burning becomes a source of carbon to the atmosphere.
- **The burning of fossil fuels is also a source of carbon to the atmosphere.** As people burn fossil fuels, this stored carbon is being rapidly released back to the atmosphere as carbon dioxide, causing the concentration of carbon dioxide in the atmosphere to increase to its highest levels in recorded history.
- **Increases in global temperature are limiting the ability of the ocean to act as a carbon sink.** Warm water holds less carbon dioxide than cold water, so some of the carbon stored in the ocean may be released back to the atmosphere as ocean temperatures rise as a result of global warming.

The changes that people are making in the global carbon balance are the most likely cause of global warming. Scientists have been recording the concentration of CO_2 in the atmosphere from an observatory at Mauna Loa, Hawaii, since 1958. They can measure CO_2 concentrations prior to 1958 by drilling into the Antarctic ice and analyzing the conditions that existed when the ice was formed. From these data, scientists know that humans have increased the amount of CO_2 in the atmosphere by 50 percent since the Industrial Revolution. And when they compare the CO_2 concentration to changes in the average global temperature, the pattern of CO_2 and temperature is almost an exact match.

The reason that increasing CO_2 in the atmosphere leads to increases in global temperatures can be explained by the *greenhouse effect*, which is shown in Figure 20-5. When energy from the sun travels to the Earth, most of it reflects off the surface of the Earth and goes back out to space as heat. Some gases in our atmosphere, however, absorb some of this energy and bounce it back to the Earth's surface.

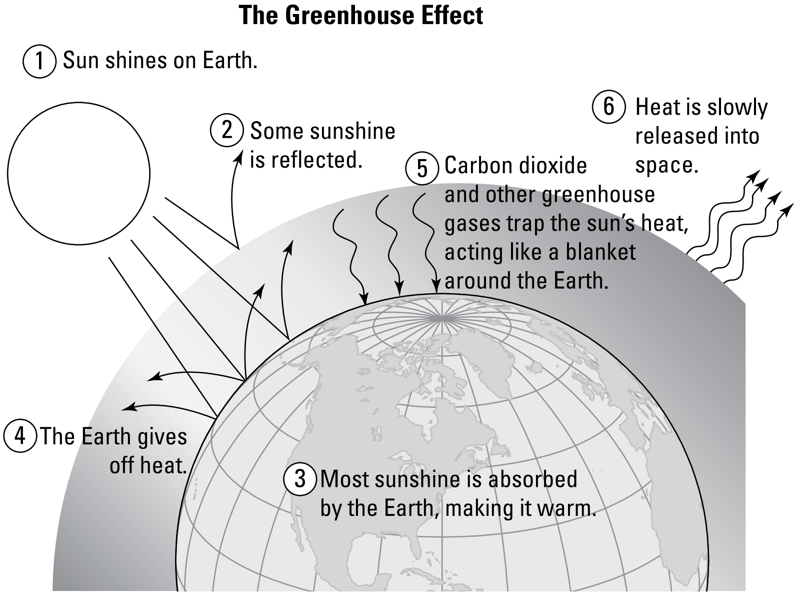

The Greenhouse Effect
① Sun shines on Earth.
② Some sunshine is reflected.
⑥ Heat is slowly released into space.
⑤ Carbon dioxide and other greenhouse gases trap the sun's heat, acting like a blanket around the Earth.
④ The Earth gives off heat.
③ Most sunshine is absorbed by the Earth, making it warm.

FIGURE 20-5: The greenhouse effect.

REMEMBER

Greenhouse gases trap energy as it travels from the Earth's surface toward outer space, reflecting that energy back toward the Earth's surface. This keeps the energy around the Earth for a longer period of time, helping the Earth to stay warm. Some of the most significant greenhouse gases are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Without any greenhouse gases, the Earth would be a cold rock in space, much like the moon. However, as people rapidly increase carbon dioxide in our atmosphere, we increase our global temperatures and cause shifts in the patterns of wind and currents. As a result, we see more severe weather events.

The nitrogen cycle

Nitrogen is essential to life because cells need it to build the amino acids that make up proteins and to make DNA and RNA.

REMEMBER

Biological nitrogen fixation occurs when nitrogen-fixing bacteria convert nitrogen gas from the atmosphere into forms of nitrogen that can be used by living things. When nitrogen fixation occurs, organisms recycle the nitrogen through ecosystems, moving it through food webs and back to the atmosphere, forming a pathway of nitrogen called the *nitrogen cycle*.

Figure 20-6 presents the key processes that transfer nitrogen through the nitrogen cycle:

- **Nitrogen fixation changes atmospheric nitrogen into forms of nitrogen that are usable by living organisms.** Nitrogen gas in the atmosphere can't be incorporated into the molecules of living things, so ecosystems depend upon the activity of bacteria that live in the soil and in the roots of plants. These *nitrogen-fixing bacteria* convert nitrogen gas (N_2) into forms like ammonium or nitrate ions (NH_4^+ or NO_3^-) that can be used by living organisms. Some nitrogen fixation also occurs by lightning strikes and by processes in factories that produce chemical fertilizers for plants. However, the nitrogen fixation that occurs from lightning strikes isn't enough to supply ecosystems with all the nitrogen they need, and industrial nitrogen fixation requires a lot of energy.
- **Producers get nitrogen by absorbing ammonia and nitrate along with water.** Plants absorb ammonium and nitrate ions through their roots as they take water from the soil. Aquatic producers like green algae can absorb ammonium and nitrate ions from the water around them.
- **Consumers get nitrogen by eating other organisms.** Consumers break down the proteins in their food and use the amino acids to build their own proteins. Consumers release excess nitrogen as nitrogen-rich waste compounds, such as urea, uric acid, and ammonia.
- **Decomposers get nitrogen by breaking down dead matter, releasing some nitrogen back to the soil in a process called *ammonification*.** As decomposers break down the proteins in dead things, they may not need all the nitrogen from those proteins for themselves. If the decomposers have excess nitrogen, they will release some of it as ammonia (NH_3) into the soil. Ammonification also occurs when bacteria convert the waste products of animals such as urea or uric acid into ammonia in the soil. Once ammonia enters the soil, it reacts with water to form the ammonium ion (NH_4^+).
- **Bacteria change the form of nitrogen as they use molecules for their energy metabolism.** Certain bacteria can get energy by converting ammonia (NH_3) into nitrite (NO_2^-), or by converting the nitrite (NO_2^-) into nitrate (NO_3^-).
  - Other bacteria in the soil use nitrate ion (NO_3^-) instead of oxygen to do cellular respiration (see Chapter 6). When these bacteria use nitrate, they convert it into nitrite ion (NO_2^-) that's released into the soil or into nitrogen gas that's released into the atmosphere.

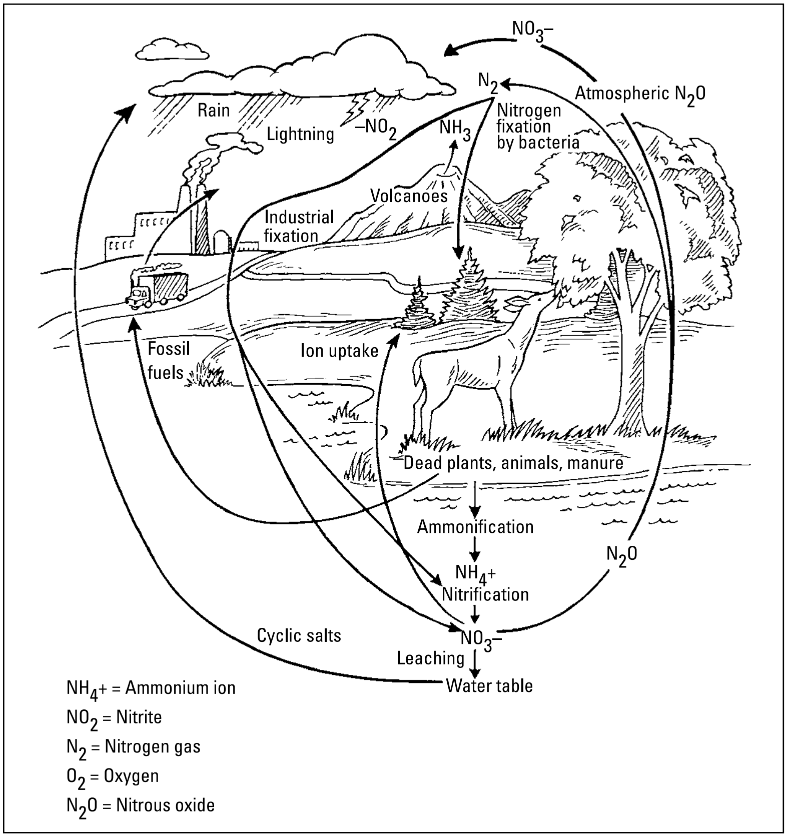

NO3–
N2
Atmospheric N2O
Rain
Lightning
–NO2
NH3
Nitrogen fixation by bacteria
Volcanoes
Industrial fixation
Fossil fuels
Ion uptake
Dead plants, animals, manure
Ammonification
NH4+
Nitrification
N2O
NO3–
Cyclic salts
Leaching
Water table
NH4+ = Ammonium ion
NO2 = Nitrite
N2 = Nitrogen gas
O2 = Oxygen
N2O = Nitrous oxide

FIGURE 20-6: The nitrogen cycle.

Interacting with Other Organisms

Organisms are constantly interacting with each other in ecosystems as they work to get the matter and energy they need to survive. These interactions can be between members of the same species (*intraspecific interactions)* or between members of different species (*interspecific interactions*). Because these interactions occur within the ecosystem, they can influence interactions between other individuals and even affect the structure of the ecosystem itself.

Working it out

Interactions between organisms can be broken down into several different types:

- ***Competition* occurs when two individuals negatively affect each other by reducing access to resources**. Resources, such as light, water, space, and minerals, are usually limited within ecosystems, and organisms must compete with each other to get what they need to survive. Competition among plants for resources can lead to reduced plant size and decreased reproduction. Competition may occur for a short time or for the life of an individual.

- ***Predation* occurs when one organism, the *predator*, kills and eats another, the *prey*.**
- ***Herbivory* is similar to predation, but perhaps more relevant to plants.** It is when one individual, the *herbivore*, feeds on all or part of a photosynthetic organism.
- ***Symbiosis* translates to "living together."** It refers to a long-term partnership, where two organisms live together for a significant part of their life cycle. Symbiosis can be positive or negative for the organisms involved.
  - *In a* mutualism*, both organisms benefit.* For example, fungi in the soil form partnerships with plant roots. Fungi called mycorrhizae grow on, and even within, the plant roots. The mycorrhizae help the roots absorb water and minerals (especially phosphates) from a wider area within the soil. The mycorrhizae benefit from the relationship because they get some sugar from the plant.
  - *In* parasitism*, one organism benefits at the expense of the other.* Some species of mistletoe are parasitic, growing on other plants and stealing water and minerals from them.
  - *In* commensalism*, one organism benefits, whereas the other is not affected.* Epiphytic plants that grow on rainforest trees benefit by gaining access to the sunlight at the top of the forest canopy without negatively impacting their host plant.
  - *In* amensalism*, an organism has a negative impact on another without being impacted itself.* Amensalism happens when one plant slows the growth of another by shading it from the sun. Some plants engage in a special kind of amensalism called *allelopathy*, where one plant releases a chemical that inhibits the growth of another. For example, plants may release chemicals into the soil that prevent seeds of other plants from sprouting.

WARNING

Some people use the term *symbiosis* in a nonscientific way to mean a relationship that is positive for both parties (scientists call this a *mutualism*). But to scientists, symbiosis doesn't always lead to mutual benefit — if you had a parasite living in you that would technically be a symbiosis. So be sure you use the term correctly when you're in a science class!

THE LOSS OF AN AMERICAN ICON

The forests of Eastern North America were once home to stately American chestnut trees, which people loved for their beauty, their nuts, and their wood. Then, in the late 19th century, plant material imported into the United States from Asia brought an unwelcome hitchhiker — the chestnut blight fungus, *Cryphonectria parasitica*. Although Asian chestnut species are resistant to this fungus, the American chestnuts had no defenses. The parasitic fungus decimated the American forests, and by 1950, all that remained of the once glorious American chestnuts were tree stumps and shrubby root sprouts. The trees have struggled on, producing new sprouts that live for a few years until they're attacked and killed by the fungal parasite.

Unfortunately, this story has been repeated many times in history. As people move around the globe, we bring other organisms with us, intentionally or unintentionally and upset the balance of interactions in ecosystems. One of the latest victims is the sacred *ʻōhiʻa* tree in Hawaii, which is under attack from a fungal parasite. Scientists are searching for methods to control invasive parasites and save native plants. You can read about some of the efforts to save the American Chestnut tree on the website of the American Chestnut Foundation at `https://tacf.org/`.

6

The Part of Tens

IN THIS PART . . .

Meet plants that dare to be different, like a plant that doesn't photosynthesize and one that "eats" insects

Discover plants that are excellent mimics of all sorts of things, from rocks and insects to rotting flesh

Get tips on how to get the most out of a botany class

Find out about the best methods for studying botany and other sciences

IN THIS CHAPTER

- Checking out the tricks plants use to control insect behavior
- Discovering that there's more to plant life than photosynthesis
- Marveling at the strategies plants have for protecting themselves

Chapter 21

Ten Weirdest Plants

Plants just sit there, so they're kinda boring, right? Not so! This chapter presents ten ambassadors from the plant kingdom to prove it to you.

Plants That Eat Insects: Cobra Lily

Plants that eat insects have many clever tricks to lure and trap their next meal (which they need to supply minerals that are lacking in the environments where they grow). The cobra lily, *Darlingtonia californica*, is a master of silent death. The leaves of the cobra lily are folded into a tube that bends over, forming a shape like the head of an upraised cobra. It even has two little flags of leaf that stick out to the sides at the bottom of the head, looking a little like fangs.

But while the whole cobra-like appearance is cool, that's not what tricks the insects. They're lured by the sweet smell that the cobra lily releases. The insects investigate and find an opening in the base of the curved tube, near what would be the cobra's mouth. They enter the leaf and are disappointed to find nothing to eat, so they decide to leave. The insects look for the light to tell them where the exit is, and they see little windows of light at the top of the plant. They fly toward the light, only to find that these are false windows, mere thin areas in the leaf that let the light through but aren't actually open to the outside. The confused insects beat their heads against the windows, trying to fly out. They grow tired and fall back to the slippery sides of the leafy tube. If they decide to try to climb out, they're confronted with sharp hairs that point downward at them from the sides of the leaf and a slippery substance on the sides of the tube. The insects may try climbing for a while or switch back to flying, until, exhausted and hopeless, they fall to the bottom of the leaf. Then, at night, the cobra lily raises the level of water — water plus digestive enzymes and bacteria — breaking down its insect meal. The cobra lily silently absorbs the minerals it needs from the corpses of its prey, patiently waiting for a new day to bring it more victims.

Plants That Stink: The Corpse Flower

The corpse flower, scientifically known as *Amorphophallus titanum,* is pollinated by flies. And what do flies like? Nasty things, like rotting meat. When the corpse flower blooms, it grows a massive spear-like inflorescence that grows up to around six feet in height and is a dull, red, meat-like color.

And because the visual isn't enough to get the job done, during the peak of its bloom the flower puts out an enormous stench designed to convince the flies that the dull-red stinky inflorescence is actually the real thing, and they should come check it out. And when I say enormous, I mean mind-boggling amount of stench. I've heard stories of the plants being moved outside of the greenhouses where they live when they're at the peak of their powers because the people who work in the greenhouses can't take the stink. I've also seen pictures of people standing next to *Amorphophallus* in bloom — wearing gas masks! And yet, when one of these plants blooms, which only happens every few years, it often makes the newspaper and people — literally, thousands of people! — come from miles around to see it. After all, it's not every day you can see the largest, smelliest plant in the world.

Plants That Move: Galloping Moss

Many plants move — Venus flytraps snap shut on their pray, sensitive plants fold up their leaves, vine tendrils swivel to find something to hold on to. But as a representative of plants that move, I've chosen a plant that travels from one place to another. A cute, spiky little green moss, named *Grimmia ovalis,* actually slides across the surface of the ground, traveling slowly downhill over the surface of lichen-encrusted rocks in the Arctic. The movement is very slow, and scientists think it may be propelled by the freeze-thaw cycle on the rocks (so maybe I'm cheating a little), but the mosses leave behind a clear trail that shows where they've been. So, when you look at the rocks, it looks like a moss race track, with clumps of moss trailing streaks of cleared rock behind them. Which is totally cool. Other plants that are growing on the moss clump get a free ride. I can imagine these mosses speeded up a little bit and starring in a children's book. As Dr. Seuss might say, "From here to there and there to here, galloping moss is everywhere."

Plants That Mimic Rocks: Stone Plants

Plants have many strategies to avoid predation, like thorns, spines, and nasty secretions. One plant that's a master of the subtle defense is the stone plant, genus *Lithops* (*litho-* means stone). Stone plants are rock-colored — dull greys and tans — and have two thick succulent leaves that are broad and flat at the top. The plants live in the desert, literally buried up to their necks — okay, the top of their leaves — in the desert soil. Only the flattened tops of the leaves are visible on the soil where they look pretty much like rocks. Any wandering animals that might be looking for juicy plants in order to get some water will just walk on by.

Of course, being buried in the soil presents some problems, such as getting enough light for photosynthesis. But the stone plants solve this problem by having thin spots in the tops of their fleshy leaves, little windows in effect, that let light into the interior of the leaf. Photosynthesis happens within the leaves below the soil. Stone plants have other names, too, including pebble plants and living stones, that illustrate just how successful their rock mimicry is.

Plants That Come Back From the Dead: Resurrection Plant

Well, the resurrection plant actually comes back from the "looks dead." But it's pretty amazing just the same. The plant, which scientists call *Selaginella lepidophylla,* lives in the deserts of North and South America. When it rains, the plant grows rapidly, producing a rosette of green branches. When it's not raining, the plant starts to curl up, and its outer branches dry out. The plant continues to roll up until it looks like a ball of dead, dried-up branches. If you found this plant in this state, you'd think it was dead and fried by the sun. But inside the center of the ball, the plant is conserving its last bit of water. The branches are dormant, but not dead, and can stay in this dormant, dried-up state for years. When the rains return, however, it turns green again and begins to unfold and grow.

Plants That Just Look Strange: Welwitschia

There's nothing quite like a *Welwitschia* plant. The plants grow only two leaves from a single stem for their entire lives, which usually last about 500 years! And during that time, the two leaves keep growing, and growing, and growing.

The plant is low to the ground — the stem bases get about two feet high or so — and the big, strappy leaves keep growing outward from the base, getting longer and longer, like wide green ribbons flowing away from the central stem. The leaves get torn and split over time, and they curl and twist in interesting arrangements around the stem. The plant ends up looking like some large, strange, alien creature that might start walking across the desert toward you.

Welwitschia is a gymnosperm, so it makes cones when it reproduces. Each plant is either male or female, but not both. When the plants are reproducing, they form cones in a ring around the stem base. These stick up looking a little like the antennae or stalked eyes, really completing the alien creature look the plant seems to be going for.

Plants That Aren't Green: Ghost Pipe

Everyone knows that plants are green. Even if they have other colors, too, somewhere they're green. Not so with ghost pipe (*Monotropa uniflora*). These small, ghostly looking plants are pure white. The plants have slender stems that grow to reach between five and ten inches in height, and they have a single, delicate, bell-shaped flower that nods downward on the stem. The plants are so white, they almost look like wax; some people even call them *corpse plants* because of this white, waxy appearance. Other people mistake them for fungi. But, no, they're plants.

You might wonder how the ghost pipe survives; after all, no green means no chlorophyll, means no photosynthesis, which means no food. The plants have very cleverly solved this minor difficulty by tapping into a fungus that lives in the soil. The plant's roots connect to the fungal cells that are growing as threads throughout the soil.

And this is not just any fungus. It's a type of fungus called *mycorrhizae* that has a special relationship with a nearby tree. So, the ghost pipe taps into the fungus, which is tapped into a tree. The fungus and tree have a working relationship — the tree gives the fungus sugar from photosynthesis, and the fungus helps the tree get water and minerals. The ghost pipe doesn't help anyone do anything; it just taps into the fungus and helps itself to all the goodies that the tree and fungus are sharing.

Plants That Have Sex with Insects: Australian Tongue Orchid

I just love orchids, don't you? Their flowers have such interesting shapes and colors, and they make me think of exotic locales. But no matter how much you or I love orchids, we don't love orchids the way orchid dupe wasps do. In particular, the wasps love a species of orchid called the Australian tongue orchid, scientific genus *Cryptostylis.* The orchids lure the male wasps with their scent and appearance, which is styled to mimic a female wasp. The orchids that have the best copycats are most likely to get pollinated by the visiting wasps, so over time, the orchids have gotten very, very good at mimicking a female wasp. The male wasp smells the alluring scent of a female wasp, looks around and sees (with its ability to see ultraviolet light) patterns on the orchid flower that look just like the patterns on a female lovely of its own species. The wasp concludes that the orchid is the source of the enticing, come-hither smells, so it buzzes on over.

Until recently, scientists thought that the wasps just attempted to mate with the orchid, but then would get discouraged and leave (carrying their load of pollen, which was the goal of the plant). But one scientist who was studying the wasp-orchid relationship thought that the mating looked pretty close to the real thing. So, after wasps were finished visiting flowers, the scientist and some of her colleagues rushed the orchid flowers to the lab to examine just how far things really went. When they looked into the flowers with a microscope, they saw swimming wasp sperm! I guess the only question remaining is how long the relationship will last.

Plants That Really Know How to Grow: Queen Victoria Water Lily

The leaves of the Queen Victoria water lily *(Victoria amazonica)* can grow to over 8 feet in diameter! And the leaves grow fast — at one horticultural pond, the leaves increased from covering 5.9 square feet of water surface to 35 square feet in just a two-week period. The leaves float on the surface of the water with the help of the network of veins that form a web over the back of the leaf. Pockets of air form between the veins, acting like little balloons to float the leaf. The back of the leaf is also covered with vicious spines that help protect the leaves from predators that live in the water.

When the lily blooms, it makes a lovely white flower about the size of a soccer ball. The flower opens at night as a female, heating up to send its pineapple-like scent out to attract scarab beetles to enter the flower. In the morning, the flower closes, trapping any visiting beetles inside. The next night, the flower re-opens, but as a male flower that is now pink. As the beetles leave the flower, the anthers of the male flower release pollen, dusting the beetles so that they'll carry pollen to the next flower.

As beautiful as the flowers are, it's the leaves of the Victoria lily that people like to see. If you search for this plant on the Internet, you'll find pictures of the enormous leaves with children sitting on them. The leaves are so large that if you distribute the weight of a child across the surface, they can easily float there.

Plants That Climb: Banyan Tree

The rainforest is lush and green, so crowded with plants, in fact, that competition for light can be fierce. Plants grow on top of other plants in order to make their way into the tree canopy where the light is. Some plants spend their whole lives in the canopy as epiphytes, never putting roots to soil. Other plants start out in the soil and then grow upward as vines until they reach the canopy. But the banyan tree has an unusual strategy that combines a bit of both.

Banyan trees start off up in the canopy, germinating on branches of other trees from seeds that have been dispersed by birds. At first, the banyan seedlings live as epiphytes, using their roots to collect water and nutrients up in the canopy. The roots of the banyans, which are prop roots, continue to grow slowly downward, twisting around the host tree as they go. Once the roots reach the soil, everything changes. The banyan trees grow faster, sending out a network of roots that fuse together and surround the host tree. The banyan outcompetes the host tree for water and nutrients. The leaves of the banyan tree spread out, cutting off light from the host tree. The host tree dies, strangled to death by the banyan, which is why the banyan is also called the strangler fig. The host tree gradually decomposes, leaving just a hollow core on the inside of the banyan. Banyan trees can get very large — one tree in Burma grew to cover 4 acres and made 1,000 prop roots.

IN THIS CHAPTER

- **Figuring out the best strategies for lecture and lab**
- **Perfecting your study habits**
- **Challenging yourself with different kinds of questions**

Chapter 22

Ten Tips for Improving Your Grade in Botany

Botany is a science, and like all sciences, it requires you to memorize a lot of specialized terminology and detailed processes. To do well, you need to find the best study strategies that work for you. In this chapter, I present ten tips to ensure that you're using your time effectively and getting the best grade possible.

Engage Actively During Class

Class time may include a lecture or activities, each of which requires a different set of skills if you want to get the most out of them. You can easily lose your focus during a lecture, letting your brain drift away to other things. The opposite can happen during activities: You can be so busy getting things done that you don't stop to think about what it all means. Both outcomes are common and could decrease the impact of your class time on your learning. Fortunately, you can do a few things to make the best of both types of class time:

- **Stay focused during lecture.** This can be challenging, as it is normal for your brain to wander onto different topics. One piece of good news is that most people can improve their ability to focus by practicing. In other words, the more you try to stay focused, the better you get at it. Another thing you can do is look for a strategy that helps you stay focused on the lecture, such as writing everything your instructor says, doodling, or trying to capture main points. (Even if your instructor gives you a printout of their presentation, try annotating it by summarizing main points in your own words or jotting down questions.)

- **Fully engage during activities.** Do the activity, but also pay attention to the questions that go with it. If you don't understand something, ask a classmate or your instructor for help. If you do understand, try to explain it to a classmate. Explaining something to someone else is one of the best ways to learn and to check your understanding. If you are working with a group on an activity, be aware of your participation. If you are naturally shy, try to push yourself to speak. If you are naturally talkative, ask others questions and try to give space for them to answer.

Use Your Lab Time Effectively

Lab is an opportunity for you to experience the material in another way, which can really help you learn. But lab also has its own challenges, especially if you have to prepare to take a lab exam called a *lab practical.*

When you're in lab, be sure to

- **Make clear drawings that are useful to you when you study.** Clear, useful sketches are particularly important if you have to take a lab practical where you're shown samples from your previous lab work and asked to answer questions about them. Often, the only thing you'll have to study from is your own lab notes and drawings. You don't have to be a gifted artist to make useful lab drawings — you just need to draw fairly clearly, use lots of labels, and make notes to yourself to help you remember. For example, if you're drawing pine pollen and you think it looks like Mickey Mouse, you could draw pollen, label your drawing, and jot a note off to the side of your page that says, "Pine pollen looks like Mickey Mouse." Then when you're studying for your lab practical, you can study your own tips and clues. So, when you take the practical and look at a slide of pine pollen even if you don't remember your drawing very well, you might remember your tip to yourself and successfully identify the pollen because it looks like Mickey Mouse.
- **Get as much help from the teaching assistant or professor as you can.** Depending on where you go to school, your professor may not teach the lab section of your course. If you attend a big school, a graduate teaching assistant often runs the lab. Teaching assistants are often easier to approach than professors, and they know a lot about what you're learning. So, ask them for help with lab stuff and with lecture material you don't understand. You

can ask them these questions when you have time in lab or during their office hours.

- **Don't leave lab early unless you've done everything fully and completely, including answering all the questions.** Sometimes, you may be tempted to cut things short and head out early, but if you do, you're wasting precious learning time. Lab gives you the opportunity to look at examples of what you're learning, touch them, and discuss your ideas with your lab partners and your professor or TA.
- **Choose your lab partners wisely.** If you're easily distracted into chatting about nonbotanical subjects, don't partner up with people who'll encourage that behavior. Try to partner up with people who do the lab work thoroughly and cooperatively and who'll stay focused on the subject for the lab.

Plan Your Study Time

The general rule for college science classes is that you should spend two hours outside of class studying for every one hour you're in class. So, the number one thing you should do every week is to make sure that you reserve enough study time. You'll get the best bang for your study time if you're smart about how you schedule it:

- **Plan for studying like you do for other important events.** Make studying a priority and figure out how to fit it into your life.
- **Schedule enough time each week.** Science classes typically require more study time than other types of classes.
- **Schedule multiple blocks of time throughout the week rather than one big cram session.** Studies show that you get the most out of studying your lecture notes the sooner you review them after lecture. So, plan some study time every day so that you can do a review before you forget what you heard. When you sleep at night, your brain edits your experiences for the day and stores only some things in long-term memory. By studying soon after lecture, you give yourself the chance to clarify your notes before you forget material. By studying in repeated short blocks, you will be practicing "spaced retrieval," which has been shown to improve retention of the material.
- **Find the best study strategies for you.** Some people learn best from pictures, some from sounds, and some from moving around. You may have one way that works best for you, but chances are you can learn from all these approaches. So, when you're studying, mix it up a bit. Draw pictures, talk out loud, act out processes using the objects on your desk, or get up and move

around. Also, relate the information you're learning to your own life or things you've heard in the news. The more neurons you can engage while you're studying, the better your understanding is likely to be.

Be Active, Not Passive

If you understand what you're hearing in class and reading in your text, that's great! Understanding is one of the first steps to learning the material. But it's only a first step. Unless you have a photographic memory, you're going to have to do some work to make the knowledge your own:

- **Put things in your own words.** Memorizing a definition from the book or an explanation from instructor will only get you so far. You can say the same thing many different ways, and your instructor is likely to use different ways of phrasing things in lecture and on exams.
- **Alternate between studying the information and testing yourself**. After you study a topic, try to recreate it for yourself. Practice drawing diagrams on blank pieces of paper, looking at your notes only when necessary. The key is that you're alternating between information storage and information retrieval. Studies on learning have shown that retrieval practice helps improve recall, such as writing out explanations.
- **Try teaching the subject to "someone else."** Ideally, you would try to teach the subject to a classmate or other person who would ask questions. But if you don't have a study group, you can just talk to your pet or even yourself. Trying to explain something helps you discover where you have good understanding and where you still need to improve. Then, go back and try to work on the areas where you need improvement.

Make Up Tricks to Jog Your Memory

Like most science classes, botany is full of new terms and processes you'll need to learn. There's really just no way around it. One way you can help yourself is to make up words or sayings to help trigger your memory of terms and events. For example, way, way, back in the fourth grade, I learned HOMES to represent the Great Lakes of the United States. To this day, I still know HOMES represents Huron, Ontario, Michigan, Erie, and Superior. You can make up your own memory tricks, get them from friends, or look online. (The fancy term for a memory trick is *mnemonic device*.)

Prepare for Different Kinds of Questions

If you're taking a course in botany, then you're probably not an expert in the subject. To get from beginner to expert, you need to do a lot of learning on different levels. And you need to be prepared to be tested at various levels of understanding. On an exam, you may be asked to

- **Recall facts.** You have to learn many terms for different structures and processes in botany. Before you can move on to higher levels or even understand your instructor, you need to learn the language of the subject. You'll be tested at this level by questions that ask *what* things are. Questions that test factual knowledge may ask you to "name," "recall," "identify," or "label." To prepare for recall questions, you can make flash cards and test yourself, practice labeling drawings, or make lists of the characteristics of plant groups.
- **Demonstrate understanding.** You may be asked to describe a process or explain something in your own words. You can prepare for these types of questions by describing a process out loud, drawing it on a blank piece of paper, or thinking of real-life examples that illustrate a process.
- **Apply information to solve new problems.** You may be asked to predict the outcome of something or identify the problem in a given situation. If your instructor used graphs to explain certain concepts, be sure to study the graphs and redraw some of them so that you understand how the graph illustrates the concept. Solve the harder problems at the end of the chapter in the text, review any problems given in class, and do any homework that was assigned.

Remember the Supporting Material

Textbooks come with lots of good and useful supporting materials these days — CDs, websites, practice tests, student study guides, and more.

WARNING

The supporting materials that came with your text were probably written by someone other than the textbook author or your instructor and may not be at the same level as your course. If a practice test is heavy on recall, but your instructor tests at a higher level of understanding and application, the practice test may give you a false sense of confidence before an exam. Definitely take advantage of whatever materials come with your text, but you need to evaluate them carefully first! If your instructor recommends a specific website, be sure to check it out.

Test Yourself Often

The big test day will come, and you'll get a permanent grade. Before you get to that crucial moment, make sure that you've put yourself through your paces in a less stressful situation. Test yourself during study sessions and get together with other students in the class to test each other. Make sure that when you test yourself, you're practicing different types of questions. (See the earlier section, "Prepare for Different Kinds of Questions.")

REMEMBER

If your instructor releases old exams, use them as practice tests after you've studied the material and think you're ready. Don't just read the practice test and the answers — it's too easy to think "Oh, yeah, I get that." Sit down and take the test like it's the actual test and see how you do.

Use Your First Test as a Diagnostic Tool

You won't really know how your instructor tests until you take your first test, unless you've had that instructor in the past (or know someone that has). Some instructors include recall questions in their tests, whereas others just write problems for you to solve.

Your first test is a very valuable piece of information. When you get your graded test, go over it and look for the types of questions your instructor asked. Pay particular attention to any questions you missed and ask yourself why you missed it. What type of question was it — recall, concept, application? Where was the information? Does your instructor test only off notes? Or test on concepts in the book that weren't covered in class? Is information learned in lab covered on exams?

Get Help Sooner Rather Than Later

If you're doing your best to actively follow along in lecture and you're not getting it, go for help right away even if it's the first day of class! Your instructor and teaching assistants have office hours and e-mail; don't be afraid to use them! Many schools have tutoring services as well.

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About the Author

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Dedication

To the people who got me excited about plants and fungi: Drs. Gillian Cooper-Driver, Richard B. Primack, Walt Halperin, Fayla Schwartz, and Elizabeth VanVolkenburgh. And to my sister, Alyson Gloria Falk, who helped me with my very first plant collection when I was an undergrad.

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